

# Goddard's Astrophysics Science Division Annual Report 2013

*Kimberly Weaver and Francis Reddy, Editors*  
*Pat Tyler, Graphical Editor*



NASA Goddard Space Flight Center  
Greenbelt, Maryland 20771

June 2014

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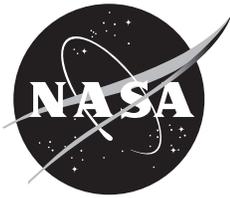
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## **Goddard's Astrophysics Science Division Annual Report 2013**

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# Astrophysics Science Division

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*Director*



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Dr. Alan Smale  
*Head, HEASARC*



Suzette Kempler  
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Officer*



Phillip Newman  
*Head, Office of Scien-  
tific Computing*

## INTRODUCTION

The Astrophysics Science Division (ASD, Code 660) is one of the world's largest and most diverse astronomical organizations. Space flight missions are conceived, built and launched to observe the entire range of the electromagnetic spectrum from gamma rays to centimeter waves. In addition, experiments are flown to gather data on high-energy cosmic rays, and plans are being made to detect gravitational radiation from space-borne missions. To enable these missions, we have vigorous programs of instrument and detector development. Division scientists also carry out preparatory theoretical work and subsequent data analysis and modeling. In addition to space flight missions, we have a vibrant suborbital program with numerous sounding rocket and balloon payloads in development or operation.

The ASD is organized into five Labs: the Astroparticle Physics Lab, the X-ray Astrophysics Lab, the Gravitational Astrophysics Lab, the Observational Cosmology Lab, and the Exoplanets and Stellar Astrophysics Lab. The High Energy Astrophysics Science Archive Research Center (HEASARC) is an Office at the Division level. Approximately 400 scientists and engineers work in ASD. Of these, 80 are civil servant scientists, while the rest are resident university-based scientists, contractors, postdoctoral fellows, graduate students, and administrative staff.

We currently operate the Swift Explorer mission and the Fermi Gamma Ray Space Telescope. In addition, we provide data archiving and operational support for the XMM mission (jointly with ESA) and the

Suzaku mission (with JAXA). We are also a partner with Caltech on the NuSTAR mission. The Hubble Space Telescope Project is headquartered at Goddard, and ASD provides Project Scientists to oversee operations at the Space Telescope Science Institute. Projects in development include the Neutron Interior Composition Explorer (NICER) mission, an x-ray timing experiment for the International Space Station, the Transiting Exoplanet Sky Survey (TESS) Explorer mission, in collaboration with MIT (Ricker, PI), and the James Webb Space Telescope (JWST).

The Wide-Field Infrared Survey Telescope (WFIRST), the highest ranked mission in the 2010 Decadal survey, is in a pre-phase A study, and we are supplying study scientists for that mission.

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## 2013 YEAR IN REVIEW

The year started off nicely with Alice Harding (ASD) and Roger Romani (Stanford) being jointly awarded the prestigious Rossi Prize from the High Energy Astrophysics Division of the American Astronomical Society (AAS). The award, for “establishing a theoretical framework for understanding gamma-ray pulsars,” was announced at the AAS meeting in January.

The Super Trans-Iron Galactic Element Recorder (Super-TIGER) balloon instrument completed a record 55-day flight in Antarctica in early February. The instrument performed very well and returned data on 50 million cosmic ray events, which will be used to measure the population of elements heavier than iron. The PI is Bob Binns at Washington University in St. Louis. The Goddard Super-TIGER team is led by John Mitchell. Goddard built the gondola and three of the four detector systems and is responsible for integration, environmental testing, logistics and payload recovery as well as participating in test, pre-flight, and flight operations. The payload is currently still on the ice in Antarctica waiting for recovery.

Development of our hardware contributions to the Astro-H mission has gone well this year. The engineering model of the X-ray calorimeter spectrometer (SXS) underwent testing in Japan and delivered expected performance (after a work-around was implemented to overcome excess detector noise due to dewar vibration). The flight model of SXS was also completed this year and was undergoing environmental testing at Goddard at year’s end. Both flight mirrors were delivered to JAXA, and testing in Japan confirmed that the mirrors exceeded performance requirements by good margins. The mirrors were built by Peter Serlemitsos, Yang Soong, and Takashi Okajima.

The WFIRST-Astrophysics Focused Telescope Assets (AFTA) Science Definition Team completed their initial report on using the donated 2.4m optical telescope assemblies for the WFIRST mission. The report was well received by Administrator Bolden, who instructed the team to continue studying the concept. Hopefully this will lead to a new mission start in ~2017. The AFTA concept now has a coronagraph that is part of the baseline mission. In late 2013, two coronagraph architectures were selected for further study. Neil Gehrels is the lead study scientist for AFTA at Goddard.

In the Spring of 2013, we were delighted to learn that both TESS and NICER were selected to continue into Phase B. TESS is an Explorer mission that will study transiting exoplanets around bright nearby stars. George Ricker (MIT) is the PI. Stephen Rinehart is the NASA Project Scientist for TESS, and Stephen and Mark Clampin (667) are members of the TESS Science Team. Goddard is also involved in Project Management and orbital dynamics. NICER is an X-ray timing instrument that will be installed on the ISS as a Mission of Opportunity. The NICER PI is Keith Gendreau and the Deputy PI is Zaven Arzoumanian, both members of our X-ray Astrophysics Laboratory. The mission is being built and managed by Goddard, with MIT (detectors), Moog (gimbal), Broad Reach Engineering (electronics) and Danish Technical University (star tracker) as partners.

The Fermi Gamma-ray Space Telescope celebrated its fifth year of operations with a party at the Goddard Recreation Center, and the Swift Explorer mission passed its ninth year in orbit. Both missions are operationally healthy and are continuing to return exceptional scientific results. I’m looking forward in 2014 to continued observations of the Galactic Center by both missions. Fermi is starting to put interesting limits on dark matter, and Swift should be getting some fabulous data when the G2 gas cloud is shredded as it passes by the Galactic Center.

We had a bit of a hiccup in October when the government shut down October 1–17. After getting back to work, it took about a week for everything to settle back to normal. Despite the shutdown, the JWST Project reported the successful completion of the first cryo-vacuum test of the JWST Integrated Science Instrument Module (ISIM) in November. The cryo-test accomplished all of its critical risk-reduction goals heading into the formal ISIM verification tests that start in 2014. See a description of JWST progress later in the document for more information.

Starting in October, Joan Centrella, our Deputy Director, spent a year on detail to the Science Mission Directorate at NASA HQ, serving in the Astrophysics Division on strategic planning for the Director, Paul Hertz. During her tenure, Joan oversaw the development of the 2013 Astrophysics Roadmap “Enduring Quests, Daring Visions,” a vision for NASA astrophysics for the next three decades. The report was a product of a community-based Roadmap team chaired by Chryssa Kouveliotou (MSFC). Aki Roberge and

Amber Straughn from our Division served on the Roadmap team, and Frank Reddy, our Science Writer, and Pat Tyler, graphics editor, supported production of the document. Hopefully, the vision described in this Roadmap will spur future investment in NASA astrophysics.

In December, NICER completed and passed its Preliminary Design Review (PDR). The review chairman noted the good character of the team and the very high quality of the review package. Unanimously, the review team reported no showstoppers and that NICER was ready to proceed to phase C (final design). The Key Decision Point-C occurs in February 2014 (sneak peek into 2014: yes, the mission was confirmed).

Finally, the year concluded with ESA selecting the science theme “The Hot and Energetic Universe” for its L2 (Large Mission 2) opportunity, with a call for mission concepts to be solicited sometime in Spring 2014. It is expected that the Athena X-ray mission concept will be chosen, although it is expected that there will be multiple proposals. The L2 launch is slated for 2028. NASA will contribute \$100–150 million in hardware, and we are looking forward to making a contribution from Goddard. The science theme “The Gravitational Universe” was selected for the L3 mission. A call for mission concepts is expected to be released near the end of this decade, with a launch date of 2034. This is certainly a long time to wait, so we are busy charting our future.

Dr. William R. Oegerle  
Director, Astrophysics Science Division

## PROJECTS IN OPERATION

### HEASARC

The HEASARC is the primary archive for NASA missions dealing with extremely energetic phenomena, from black holes to the Big Bang. Incorporating the Legacy Archive for Microwave Background Data Analysis (LAMBDA), HEASARC curates and maintains datasets obtained by missions that study the relic cosmic microwave background (CMB) as well as NASA's high-energy astronomy missions from the extreme ultraviolet through gamma-ray bands. The HEASARC archive contained about 60 terabytes (TB) of data at the end of 2013, having grown by over 10 TB during the year, and includes data from seven active missions (Chandra, Fermi, INTEGRAL, NuSTAR, Suzaku, Swift, and XMM-Newton) and from more than 30 space-based missions and sub-orbital experiments that are no longer operational. Papers written using HEASARC data comprise ~10 percent of the total astronomical literature and include some of the most highly cited papers in the field. The HEASARC Office is led by Dr. Alan Smale.

In August 2013 the NuSTAR public data archive opened at the HEASARC. Launched in June 2012, NuSTAR is a Small Explorer (SMEX) mission with the first focusing high-energy X-ray telescope in orbit. The HEASARC archive contains NuSTAR data converted into standard FITS format and documentation on the data and data analysis software. HEASARC data access tools can be used to locate and download data from individual observations, and the NuSTAR data analysis software is distributed to the community as part of the HEASARC's HEASoft data analysis suite. By the end of 2013 a total of 72

observations had been released in the archive. Dr. Francis Marshall serves as the HEASARC's NuSTAR Archive Scientist, with significant contributions to the NuSTAR archiving effort from Drs. Michael Corcoran, Stephen Drake, Thomas McGlynn, and William Pence.

The HEASARC remains a core partner in the joint NSF/NASA program to manage and operate the U.S. Virtual Astronomical Observatory. Dr. McGlynn leads the HEASARC's VAO involvement and serves as the VAO Lead for Operations. He and his staff have developed applications which monitor the health of VAO and other VO services and inform responsible parties of issues as they arise. As part of preparation for the upcoming termination of VAO funding, Drs. McGlynn and Smale have worked with representatives from other NASA archives and our VAO partners to develop a closeout repository to ensure that all digital artifacts including code and documentation are preserved. In addition, Dr. McGlynn continues his work leading the development of the HEASARC's archive interfaces and managing, developing and enhancing the Skyview virtual observatory.

During 2012, HEASARC programmers under the direction of Dr. William Pence coordinated two new releases of the HEASoft data analysis software package, providing improved analysis capabilities for data from the NuSTAR, Swift, and Suzaku observatories. The HEASARC staff also enhanced the cloud-based Hera data analysis service which enables researchers to analyze their data over the internet, using HEASoft within the computing environment provided by the HEASARC. The major focus of development has been to integrate Hera more closely with the new Xamin interface, so that

### Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Frank Marshall	Gamma-ray bursts, pulsars	Swift HEASARC NuSTAR	Co-investigator; Science Center Lead NuSTAR Archive Scientist
Thomas McGlynn	X-ray and gamma ray astronomy; interoperability; tools and techniques for astronomical research	HEASARC VAO	Archive Scientist Operations Lead
William Pence	X-ray astronomy of normal galaxies; data compression; advanced data analysis techniques	HEASARC	HEASoft Team Lead
Alan Smale	spectroscopic and timing analysis of X-ray binaries; cataclysmic variables	HEASARC PCOS	Director Deputy Chief Scientist

researchers can seamlessly query the HEASARC archive to locate relevant observations and then analyze the data using Hera, all within the same Web browser session.

Dr. Stephen Drake continued to add tables to the HEASARC's archive, bringing the total number of unique tables available at the HEASARC to ~800. Among the newly created tables seven were new Chandra source lists, fourteen were new XMM-Newton source lists, and others included data from a broad array of missions including AGILE, CGRO, EUVE, GALEX, Herschel, INTEGRAL, MAXI, Planck, ROSAT, and WMAP. Dr. Drake serves as the HEASARC's XMM-Newton and RXTE Archive Scientist, and supports the HEASARC's web pages and RSS feed.

Dr. Michael Corcoran serves as the manager of the HEASARC Calibration Database and as Fermi and ROSAT Archive Scientist. During the past year Dr. Corcoran maintained and updated the calibration database for Swift, Suzaku, Chandra, and Fermi missions, with a total of 22 updates. He worked with the Fermi LAT team to help implement full CalDB access in the Fermi Science tools and participated in weekly FSSC meetings plus telecons, and worked on documentation updates and discussions regarding Fermi calibration data. Dr. Corcoran continued to improve the implementation of the GBM response matrix generation software in the HEASARC BROWSE environment, and worked with the Fermi Science Support Center to release the calibration databases for the LAT. Dr. Corcoran writes the HEASARC Picture of the Week website, and administers a HEAPOW Facebook group which currently has over 250 members from around the world. He also maintains the Astro-Update website, used by scientists to keep track of updates to important high-energy astrophysics software packages.

Dr. Keith Arnaud leads development of the XSPEC spectral fitting tool and related software. Major improvements to XSPEC over the past year included improved support for parallel processing, the replacement of the old CERN Minuit code with the new C++ version and better integration within XSPEC, new MCMC methods, new statistics, and, as always, new models.

Dr. Steven Sturmer is responsible for maintaining the INTEGRAL public data archive at the HEASARC. This activity entails downloading the ~twice-monthly public data releases from the ISDC in Geneva and installing the data within the HEASARC archive, and overseeing the transfer of weekly metadata updates to the HEASARC. During the course of the

year, Dr. Sturmer was responsible for revising and adapting the update process as changes to the computer systems at ISDC changed and evolved.

Under the leadership of CMB Archive Scientist Dr. David Chuss, LAMBDA significantly increased its data holdings in 2013. LAMBDA now contains the complete data set for the WMAP mission that became final with the nine-year data release. Also, in support of the Decadal Survey recommendations regarding the importance of suborbital data for pioneering technology and techniques in advance of a potential Inflation Probe mission, LAMBDA added new products from the latest ground-based CMB polarimetry experiments. These include the latest data from the BICEP1 polarimeter. LAMBDA is also hosting additional data from the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT). ACT and SPT are fine-scale ground-based CMB instruments that complement space-based measurements and provide exciting probes of dark matter, dark energy, and the large-scale structure of the universe. In addition, as part of its charter to provide a comprehensive data archive for the CMB, LAMBDA now provides a portal to the Planck CMB temperature data that accompanied the 2013 data release.

## MISSION CONCEPTS

### Future Large-Aperture Space Observatories

The NASA Advisory Council's Astrophysics Subcommittee released its long-range vision, Enduring Quests, Daring Visions, which—among other priorities—highlights a large-aperture UV/visual/NIR space observatory as a future agency priority, perhaps in the 2020s. In response, Dr. Harley Thronson established a GSFC team that, in partnership with NASA MSFC, JPL, and STScI, is developing designs, identifying key technology investment areas, and assessing priority science goals for the Advanced Technology Large-Aperture Space Telescope (ATLAST). An early version of this concept was studied by many of the same people about a half-decade ago in advance of the NRC 2010 Decadal Survey. The current activity is targeting the 2020 Decadal Survey and a selection as the highest-priority major space astronomy mission for the subsequent decade.

Design work at present is concentrating on operation from wavelengths of about 0.2 micrometers

longward to 2.5 micrometers with a suite of instruments capable of carrying out a broad range of scientific programs. One very attractive—albeit extremely challenging—science goal is the search for biosignatures in the spectra of Earth-like worlds in the solar neighborhood. For this goal, an aperture of about 10 meters in diameter appears feasible and fits within currently available launch vehicles. The multicenter team is also considering the opportunities offered by a much larger launch vehicle being developed for the human space flight program.

## Human Operations Beyond Low-Earth Orbit

NASA's human space flight program, although with continuing significant uncertainty in its goals and priorities, consistently identifies operations in free space beyond low-Earth orbit (LEO) as a priority. Whether as a staging site for long-duration voyages beyond the Earth-Moon system, supporting human and telerobotic exploration of the lunar surface, or advancing technologies developed on the International Space Station (ISS), continued human operations in free space have been recommended to NASA for decades as a major enabling capability.

Dr. Thronson continues to work with a small team of scientists and engineers at Goddard, other NASA centers, and in industry, which has for several years been developing concepts for how equipment and facilities developed for human space flight might be used to achieve other goals. Such work has a long history at Goddard: In the early 1970s, Frank Cepollina and colleagues persisted in advocating that the space shuttle be adapted to service and upgrade satellites in LEO. This was almost two decades before Cepollina's team used the shuttle to rescue NASA's premier astronomical observatory, the Hubble Space Telescope. Vision and perseverance eventually pays off!

Currently, Thronson and colleagues have taken on the ambitious task of designing a long-duration human habitation system to operate in free space in the vicinity of the Moon. Its primary purpose would be to develop capabilities necessary for safe and comfortable human operations beyond LEO in the early 2020s. A variety of goals are being evaluated for this habitat, including support for lunar surface operations, either with astronauts or with telerobots, and as an exploration system for an asteroid returned to the Earth-Moon system. However, in addition, the capability to repair, assemble and up-

grade complex science facilities, including large optical systems, may also be considered.

More recently, Thronson co-chaired the Affording Mars workshop planning team, a meeting co-sponsored by Explore Mars, Inc. and the American Astronautical Society and held at George Washington University. The December 2013 workshop critically assessed options for initial human missions to Mars that appear much less costly than scenarios that have been previously developed. The workshop summary and recommendations are at <http://www.exploremars.org>.

## EDUCATION AND PUBLIC OUTREACH

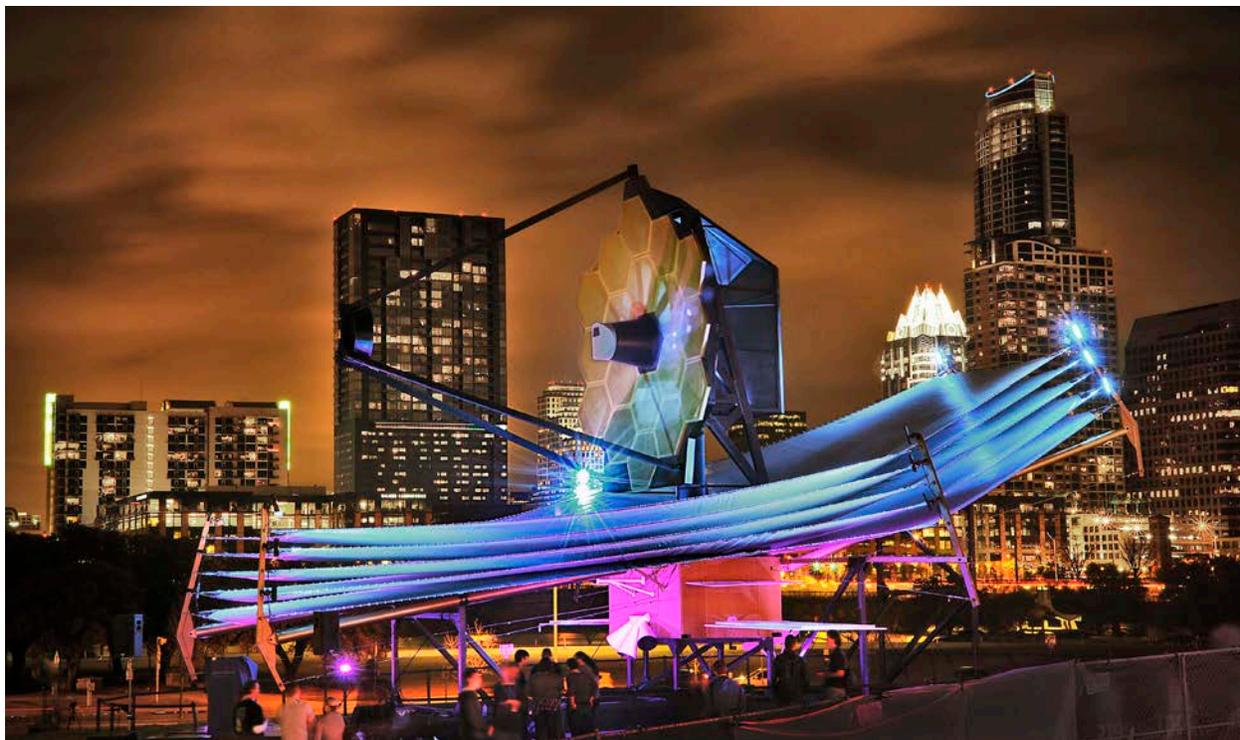
2013 was a year of uncertainty for E/PO professionals across NASA's Science Mission Directorate as the Agency reevaluated the role of education and considered options for consolidation of STEM activities. The ASD E/PO team responded rapidly to requests for information from NASA HQ and NASA's Astrophysics Science E/PO Forum. Throughout this process, our team was directed to continue developing and facilitating its programs. The ASD E/PO team is dedicated, and even while our activities were being reassessed, the team accomplished much over the past year.

The ASD E/PO team has extensive projects that align with the Physics of the Cosmos (PCOS) and Cosmic Origins (COR) program offices, and our team supports NASA astrophysics missions, including Astro-H, JWST, Suzaku, and HEASARC. Dr. Amber Straughn of the Observational Cosmology Laboratory is the civil servant Lead for the team.

## PCOS/COR E/PO

As the second fully-funded year of PCOS/COR E/PO, 2013 saw continued growth for our new initiatives and established programs, under the leadership of Dr. Barbara Mattson.

The Space Forensics project, lead by Sara Mitchell, is a cornerstone element of PCOS/COR E/PO. This project presents astronomical mysteries as detective stories, with a suite of resources for formal and informal education venues. In 2013, the team, with external science writers, completed narratives for supernovae and black holes cases. They began assembling these narratives into educator guides with the stories and related activities. The project's



*The full-scale James Webb Space Telescope model at South by Southwest in Austin. Credit: NASA/Chris Gunn*

external evaluator developed tools for assessing professional development workshops and to evaluate pilot implementation.

Big Explosions and Strong Gravity (BESG), led by Sarah Eyermann, is a highly successful outreach program developed in 2004 where children explore the science behind supernovae and black holes through hands-on activities. Though BESG was initially created in collaboration with Girl Scouts, the curriculum is appropriate for other out-of-school audiences. In 2013, the team researched the needs of potential partners and began a website upgrade to accommodate expanding the program. The BESG team also presented a workshop at the Midwest Afterschool Science Academy in Kansas City, Mo.

NASA Blueshift, led by Mitchell and Maggie Masetti, provides a behind-the-scenes look at Astrophysics at Goddard through social media and new media. In 2013, the team released blogs highlighting mission milestones, scientific discoveries, and Division scientists, interns, grad students and post-docs. During 2013, the team released seven podcasts. Blueshift also continued to connect with the public through social media, nearly doubling its Twitter following to 35,000+ followers and more than tripling its Facebook likes to 18,500+.

## **Astrophysics Missions E/PO**

### **HEASARC**

The HEASARC E/PO program continues to fulfill its mission of bringing high-energy astronomy to teachers and their students. Mattson leads the E/PO program with team members George Gliba and Meredith Gibb. The Imagine the Universe! website provides the foundation for HEASARC E/PO, with information for the general public and resources for the classroom. Mattson and Gibb began a site-wide update to bring the information on the site up-to-date with current research. During 2013, Gliba filled over 750 requests for our educational materials from educators across the country.

### **JWST**

JWST E/PO and Communications is a partnership between Goddard and the Space Telescope Science Institute, and other contractor collaborations. This has been an active year for JWST, with our largest-scale activity being participation in South by Southwest, a music, film, and technology festival in Austin, Texas. The JWST presence included on-going demonstrations, speakers, and the full-scale JWST model. The event even brought NASA a spot



*ASD outreach: Amber Straughn at the 2013 South by Southwest festival in Austin, Texas, talks to attendees about the James Webb Space Telescope's orbit using a visualization wall.  
Credit: Chris Gunn*

in the Guinness World Records for the largest astronomy lesson ever.

JWST has a strong social media presence, with efforts led by Masetti. By the end of 2013, the JWST Twitter following doubled to 105,000+ followers, their Facebook page tripled to 160,000+ likes, the JWST YouTube channel had 100,000+ video views, and the Flickr feed had nearly 500,000 views.

JWST again partnered with the RealWorld/InWorld Engineering Design Challenge, in which student teams compete in both a classroom and virtual setting, and have online interactions with project scientists and engineers. Over 850 students participated this year. The JWST flash game “Build It Yourself: Satellite” passed the NASA Education Product Review in 2013 and posted to the JWST website with 38,000+ views.

### **Suzaku & Astro-H**

This year, Astro-H E/PO, led by Mattson, continued the legacy of Suzaku E/PO. The Collaboration Across Cultures website provides continuity for audiences from one mission to the next. The Science in the Media lesson plan was pilot tested by a group of teachers from around the country and was ultimately posted to the Collaboration website.

### **Grants and External Collaborations**

In 2013, the Afterschool Universe (AU) and Family Science Night (FSN) teams, led by Eyermann and Mitchell, respectively, applied for an HST supplemental grant (science PI: Jane Rigby) to create and evaluate new sessions for these programs related to Rigby’s research. AU and FSN are well-established and thoroughly evaluated programs that were first created in 2006.

The ASD EPO team participated in the NASA-wide collaboration “NASA Science4Girls and Their Families,” which offers informal science events public libraries nationwide in celebration of Women’s History Month. The team provided resources to the Cerritos Library in Cerritos, Calif., to run an event for 10–12 year-olds in April. In addition, the ASD EPO team ran a local event at a Howard County library on March.

### **ASD Press and Communications**

Press releases and web features are the primary means of communicating ASD science news to the



*Drs. Koji Mukai and Kim Weaver prepare for the mock press conference forming the core of the Science in the Media lesson plan, which was pilot tested by teachers in 2013. Credit: NASA/ B. Mattson*

general public. The ASD Press Officer, Francis Reddy, fills this crucial role for the Division, and he produced 25 releases and features over 2013 on Fermi, Swift, and other Division-related news. Nearly half of these were accompanied by videos. Reddy also created the “Paper Model of Comet ISON’s Orbit” in conjunction with Swift observations of the comet. The model passed NASA Education Product Review and was viewed 360,000+ times.

Finally, the ASD E/PO Group Facebook page, NASA Universe Education, led by Mattson, more than tripled its following over the year to 81,000+ likes. This page features the High Energy Picture of the Week and links to the Division’s press releases and web features.

## AWARDS

Last year, several personnel received Robert H. Goddard Awards for their work in 2012. ASD Deputy Director Dr. Joan Centrella won the Mentoring Award “for her demonstrated commitment to mentoring women scientists at all stages of their careers, which has resulted in a positive and supportive professional environment for all.” Assistant Director Dr. Curtis Odell received the Safety Award “for thorough and detailed investigation into the root cause of the laboratory fire in Building 34, Room C259, and his efforts to define and implement a recovery plan.”

In addition, Dr. Barbara Mattson, the PCOS/COR E/PO Lead, was awarded an ASD Peer Award in 2013.

The Science Team Award went to the HEASARC team “for enabling new science results from NASA missions by providing high quality software for data search, retrieval and analysis through the HEASARC data archive research center” and specifically cited Alan Smale, Thomas McGlynn, Bill Pence, Frank Marshall, Lorella Angelini, Dave Chuss, Phil Newman, Keith Arnaud, Mike Corcoran, Steve Drake, Steve Sturmer, Laura McDonald, Ed Sabol, Craig Gordon, Bryan Irby, Pan Chai, Urmila Prasad, and Michael Greason.

The ASD Press Officer, Francis Reddy, was presented with the Outreach Award “for outstanding dedication to public outreach through the media, including exceptional scientific writing and coordination with NASA video producers, resulting in high-impact Astrophysics press releases and features.”

# Astroparticle Physics Laboratory



Dr. Neil Gehrels  
*Lab Chief*

## Laboratory Overview

The Astroparticle Physics Laboratory (Code 661) conducts research in cosmic ray and gamma ray high-energy astrophysics. Researchers investigate high-energy phenomena in the universe in terms of unified theories of fundamental interactions. The Laboratory conducts a broad range of space-based scientific studies of the origin, nature, and effects of cosmic rays. Researchers also observe gamma radiation that carries the signatures of physical processes at work throughout the universe. The birth and evolution of black holes and other compact objects is a key area of investigation. The Laboratory emphasizes the development of new detectors and instrumentation technologies. In addition to the civil servant staff, the laboratory has 43 contract and university scientists, engineers, technicians, post docs, and grad students.

## Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Lorella Angelini	High-energy astrophysics; Data systems	HEASARC Suzaku  Swift Astro-H	Project Scientist Deputy Project Scientist Archive Lead Archive Lead Archive/Data Center Lead
Scott Barthelmy	Gamma-ray bursts (GRBs); Gamma-ray Spectroscopy; Instrument development; Gamma-ray polarimetry	Swift GCN INFOCUS ISS-Lobster	Lead Scientist (BAT) Principal Investigator Principal Investigator
Padi Boyd	Long-term variability in X-ray binaries; Accretion disk dynamics	HST Swift	HST Deputy Project Scientist for Operations
Theresa Brandt	Particle astrophysics; Supernova remnants; Cosmic rays; Instrument development	Fermi Super-TIGER	
Brad Cenko	GRBs; Instrument development; Supernovae; Tidal disruption flares, Time-domain astronomy	Swift Fermi WFIRST-AFTA	Deputy Project Scientist  Study Scientist <i>University of Maryland JSI</i>
Tom Cline	GRBs	Swift	Emeritus
Neil Gehrels	Gamma-ray astronomy; IR astronomy; Instrument development	Swift Fermi WFIRST-AFTA ISS-Lobster	Principal Investigator Deputy Project Scientist Project Scientist <i>University of Maryland Penn State University</i>

Scientist	Research Interest	Project/Mission	Role/Affiliation
Robert Hartman	Gamma-ray astronomy	Fermi	Emeritus
Elizabeth Hays	High-energy gamma-ray sources; Instrument development	Fermi	Deputy Project Scientist <i>JSI</i>
Stanley Hunter	Galactic diffuse emissions, Experimental gamma ray astrophysics; Gamma-ray polarimetry; detector development	3-DTI AdEPT	NASA PI
Julie McEnery	GRBs; High-energy astrophysics; Instrumentation	Fermi	Project Scientist <i>University of Maryland</i>
John Mitchell	Experimental particle and gamma-ray astrophysics; Instrument and detector development	BESS-Polar CALET HELIX ISS-CREAM Super-TiGER NASA Scientific Balloon Program	NASA PI Institutional PI Institutional PI Institutional PI Institutional PI Project Scientist
Jeremy Perkins	Active Galactic Nuclei (AGN); High- energy astrophysics; Instrumentation	Fermi	
Judith Racusin	GRBs; Supernova remnants; High-energy astrophysics; Instrumentation	Fermi Swift ISS-Lobster	Deputy Project Scientist
Donald Reames	Astrophysics of energetic-particle acceleration at the Sun, in the heliosphere and in the galaxy	Wind/EPACT	Emeritus
David Thompson	Multiwavelength astrophysics, particularly of AGN and pulsars; High-energy astrophysics; Instrumentation	Fermi	Deputy Project Scientist
Tonia Venters	Astroparticle physics; Diffuse emissions	Fermi	
Tycho von Rosenvinge	Energetic particles in the heliosphere, their acceleration, composition, and transport	ACE, STEREO, Solar Probe+	Project Scientist Co-Investigator Co-Investigator

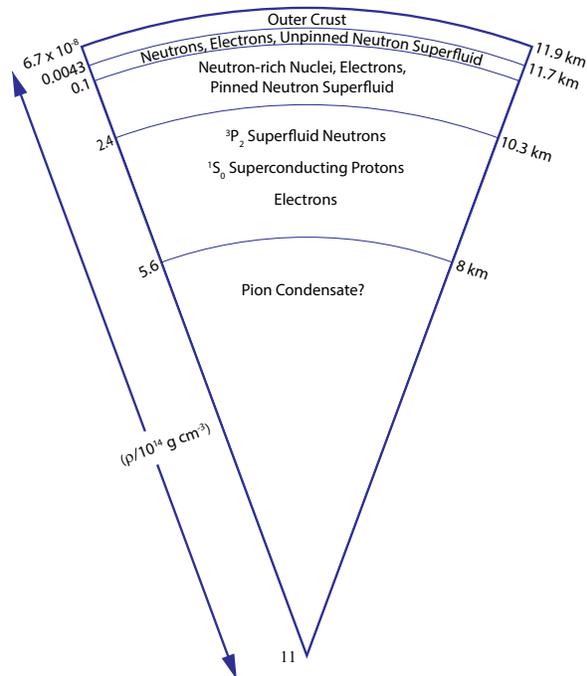
## SCIENCE HIGHLIGHTS

### First Anti-glitch detected on a Magnetar

Monitoring observations over about a one-year interval (2011.7–2012.9) of the magnetar 1E 2259+1586 using the Swift X-Ray Telescope have revealed an anti-glitch—a sudden increase in the spin period, or conversely, a decrease in the rotation rate—on April 28, 2012. This is the first clear evidence for such an event. All previous glitches have been spin-ups of the neutron star rotation rate, rather than spin-downs, and the term anti-glitch was invoked in order to contrast the two event types. The

spin period of 6.979 seconds increased by about 2.2 microseconds, a change coincident with a brief but intense burst of X-rays.

Normal glitches are thought to occur when the neutron star’s internal structure suddenly changes. Theory tells us that beneath the star’s 200-meter-thick outer crust of iron lies a neutron-rich superfluid. One of the properties of rotating superfluids is that their vorticity, or circulation tendency, is concentrated into quantum vortex lines. As the neutron star spins down with time, the quantum vortices in the deep crust become pinned to crust lattice nuclei, thereby keeping this layer rotating faster than the rest of the star. When one of these vortices comes loose in a catastrophic “unpinning”



Sketch of a neutron star's interior, after Pines and Alpar (1985).

event, the overall rotation rate increases and produces a glitch.

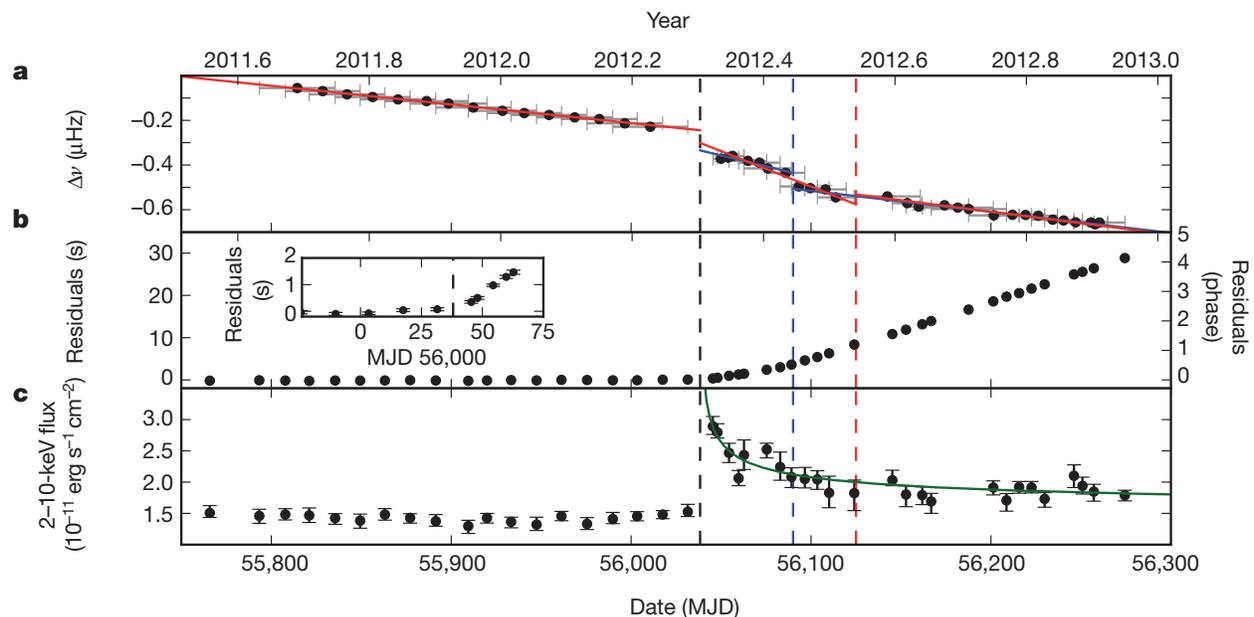
How could an anti-glitch occur? Two mechanisms were discussed in the context of the Swift detection, one internal and the other external. The internal model requires some mechanism analogous to vortex unpinning that instead taps into a slow-

er-than-average angular momentum layer inside the star. The external model invokes a sudden change in the magnetic field lines threading the neutron star and linking it to the surrounding plasma.

### Exceptional gamma-ray burst challenges our understanding of shock physics

On April 27, 2013, Fermi and Swift triggered on gamma-ray burst (GRB) 130427A, which turned out to be one of the brightest ever detected in gamma-rays. The high-energy (>100 MeV) gamma-ray observations by the Fermi-Large Area Telescope (LAT) showed several unprecedented properties, including a short initial spike coincident with the keV-MeV Fermi Gamma-ray Burst Monitor (GBM) emission, followed by relative quiet during the main prompt GBM emission over the next tens of seconds, then a peak and decay detected for nearly a day. Swift slewed its narrow-field X-Ray Telescope and UltraViolet/Optical Telescope toward the GRB, and ground-based optical telescopes began following the afterglow decay. The RAPTOR telescope observed the optical peak to an R-band magnitude of 7.4, making it the second-brightest optical counterpart to a GRB ever detected.

In the following hours, a high-resolution spectrum taken at the Gemini-North optical telescope led to a redshift measurement of 0.34, much closer than the average GRB redshift of ~2. It became



Timing and flux properties of 1E 2259+1586 since mid-2011 from Archibald et al. (2013).

apparent that GRB 130427A was not necessarily the most exceptional GRB ever observed, but rather, it was similar to its cosmological cousins, and it just happened to go off in our “backyard.” All other low-redshift GRBs detected previously had been under-luminous. As the GRB community began taking observations, other firsts included NuSTAR detecting the first late-time hard X-ray afterglow, at 1 and 5 days after the burst. As the GRB afterglow is slowly fading, it may be detectable in the radio and X-ray bands for years to come.

The detailed radio-to-GeV observations of GRB 130427A present challenges for the standard theoretical models that attribute the afterglow emission to a slow-cooling synchrotron component. Current models of shock physics seem unable to generate the late-time energetic particles needed to produce such high-energy synchrotron gamma rays.

More than a dozen papers on this object have already been published, including significant contributions by ASD staff including Sylvia Zhu, Judy Racusin, Dan Kocevski, Brad Cenko, Eleonora Troja, Julie McEnery, and Neil Gehrels

## Swift Ultraviolet Maps of the Magellanic Clouds

The Ultraviolet/Optical Telescope (UVOT) on board Swift has completed the first wide-field multi-color near-ultraviolet survey of the Magellanic Clouds. The Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) lie about 163,000 light-years and 200,000 light-years away, respectively, and orbit each other as well as our own Milky Way galaxy. The LMC is about one-tenth the size of the Milky Way and contains only one percent of the Milky Way’s mass. The SMC is half the size of the LMC and contains about two-thirds of its mass. Despite their small actual sizes, the galaxies are large in the sky because they are so close to us, and they extend far beyond the UVOT’s field of view. Thousands of images were needed in order to cover both galaxies in three ultraviolet colors between 1600 and 3300 angstroms.

The resulting mosaics show the LMC and SMC in never-before-seen detail in the ultraviolet. Nearly a million ultraviolet sources appear in the image of the LMC, which was assembled from 2,200 individ-



*Nearly a million ultraviolet sources appear in this mosaic of the Large Magellanic Cloud, which was assembled from 2,200 individual images taken by Swift’s Ultraviolet/Optical Telescope. The 160-megapixel image required a cumulative exposure of 5.4 days and covers the near-ultraviolet from 1600 to 3300 angstroms. NASA/Swift/S. Immler (Goddard) and M. Siegel (Penn State)*

ual snapshots. The 160-megapixel image required a cumulative exposure of 5.4 days. The 55-megapixel image of the SMC has an accumulated exposure time of almost two days and contains over 250,000 ultraviolet sources. The unprecedented data set is being used to look at the recent star formation history of the Magellanic Clouds, the distribution of young stellar populations over the face of the galaxies, and the location of rare stellar types such as post-asymptotic giant branch stars and unusually hot UV-bright stars. Photometry of thousands of open and globular clusters is revealing the sequences of bright main sequence stars, blue horizontal branch stars and extreme horizontal branch stars, and will be used to study the LMC and SMC's dust extinction law.

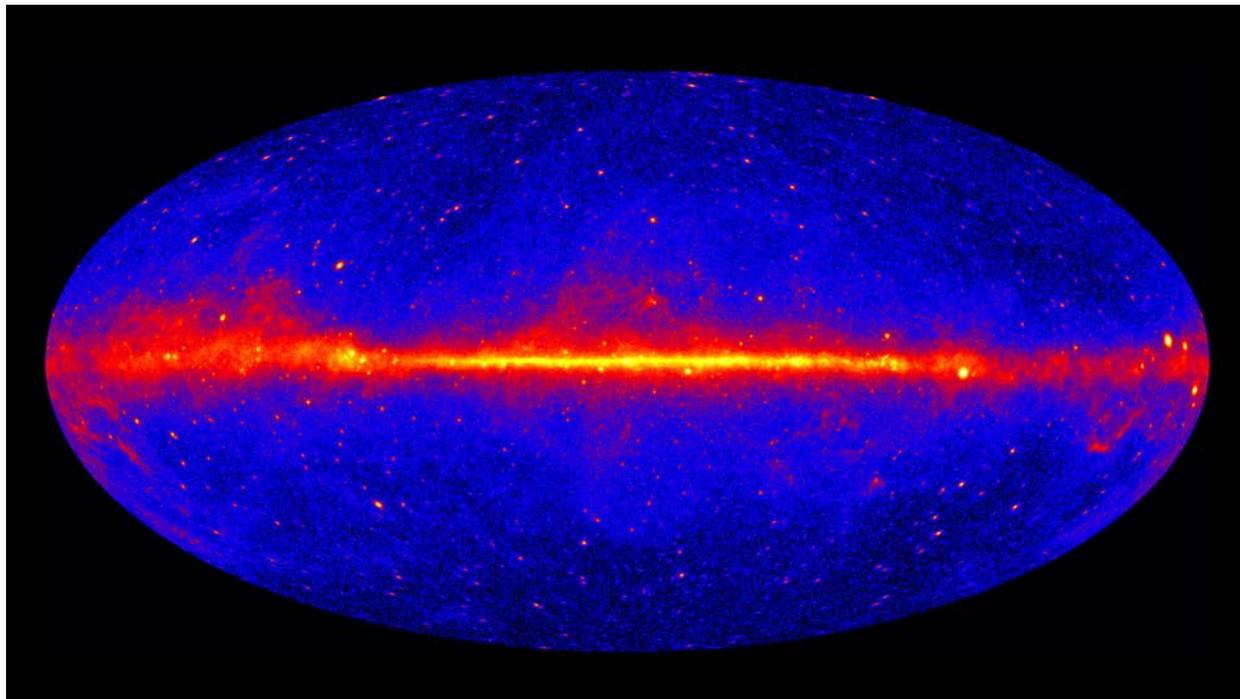
## PROJECTS IN OPERATION

### Fermi

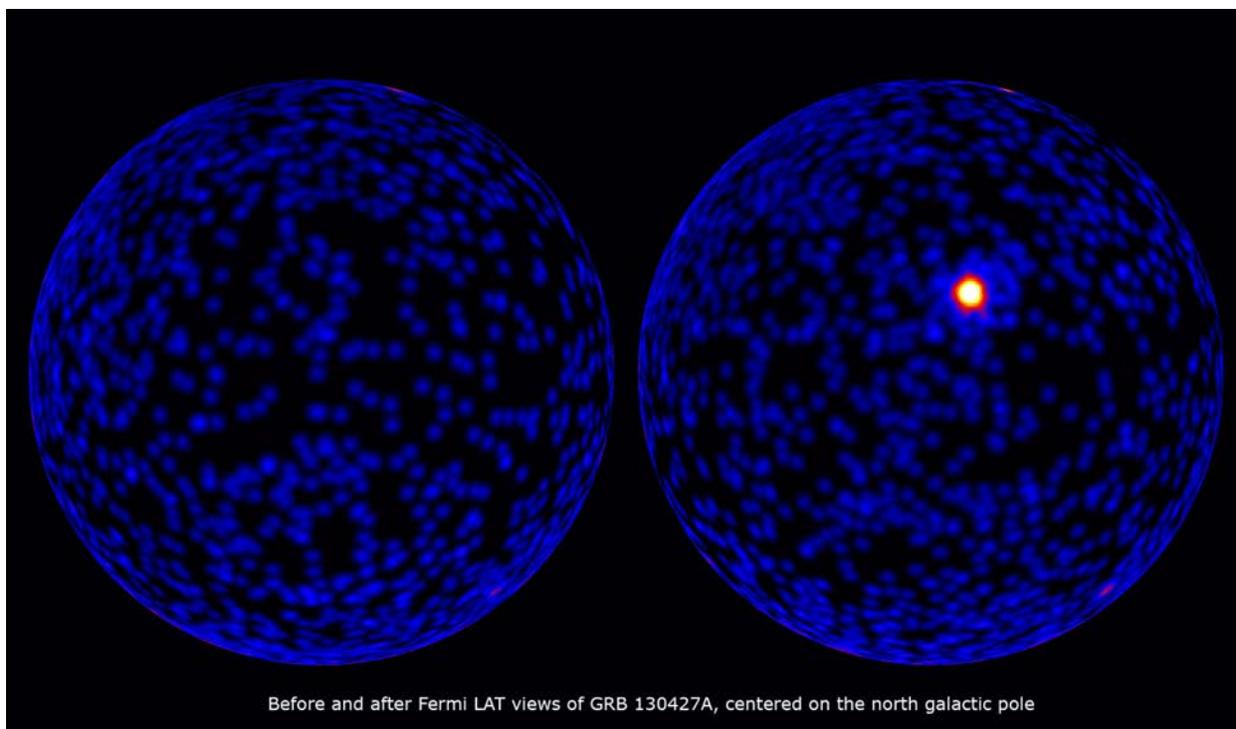
In August 2013, the Fermi Gamma-ray Space Telescope marked five years of scientific discovery and embarked on the extended phase of the mission. In honor of the anniversary, the Goddard Visitor's Center added a 1/10th scale model of the observatory and new graphical displays of Fermi science thanks to an effort led by Tonia Venters. Over the

past year, Fermi's ever-deepening high-energy gamma-ray sky survey and ongoing monitoring allowed scientists to build the most detailed map of the sky at these wavelengths and to catch extraordinary transients in action.

David Thompson and Elizabeth Ferrara with other team members have been preparing the third catalog of sources from Fermi's Large Area Telescope (LAT), containing more than 3,000 objects. Thompson, Ferrara, Alice Harding, and Megan DeCesar also contributed to the second catalog of LAT gamma-ray pulsars, containing 117 detections. Harding and DeCesar additionally studied models of pulsar emission geometry using the light curves of the brightest Fermi pulsars. Thompson, Ferrara, Fabio Acero, Roopesh Ojha, and Davide Donato focused on characterizing gamma-ray sources in the LAT catalog without counterparts at other wavelengths as new gamma-ray pulsars, active galactic nuclei, or other sources that don't fit well in either class. Acero, Jack Hewitt, Terri Brandt, and Jamie Cohen have been studying the emerging population of gamma-ray-emitting supernova remnants. The multiwavelength spatial and spectral properties of LAT-detected remnants continue to constrain and characterize particle acceleration sites in the Galaxy. David Green and Alex Moiseev have been pursuing different angles on accelerated particles through di-



*This view shows the entire sky at energies greater than 1 GeV based on five years of data from the LAT instrument on the Fermi Gamma-ray Space Telescope. Brighter colors indicate brighter gamma-ray sources. NASA/DOE/Fermi LAT Collaboration*



*Before-and-after maps centered on the northern Galactic pole at energies above 100 MeV show the dramatic appearance of GRB 130427A as seen by Fermi's LAT instrument. Left: The sky during a 3-hour interval before GRB 130427A. Right: A 3-hour map ending 30 minutes after the burst. NASA/DOE/Fermi LAT Collaboration*

rect measurements of cosmic-ray electrons and nuclei with the LAT.

Ojha, Donato, Mike Dutka, Bryce Carpenter, and Bill McConville have been watching the sky for new flares and new sites of gamma-ray emission as LAT flare advocates. They explored the multiwavelength properties of gamma-ray blazars through follow-up observations, particularly in the X-ray band and the radio band to obtain high-resolution images of jet features. Ojha and Dutka also contributed to a publication with Elizabeth Hays on a recent bright flare in the Crab Nebula. The extremely rapid variations in the gamma-ray emission have challenged modelers of pulsar nebulae including Harding to identify the mechanism at work in the magnetic structure of the Crab's pulsar wind. McConville, Jeremy Perkins, and Josefa Becerra Gonzalez have pursued very high energy follow-up for AGN detected by LAT using ground-based gamma-ray telescopes to explore some of the most energetic and rapidly varying sources in the sky.

Sylvia Zhu led a paper for the LAT team with Judy Racusin, Daniel Kocevski, and Julie McEnery on observations of the groundbreaking gamma-ray burst (GRB) 130427A. This relatively nearby outburst produced the highest fluence and highest-en-

ergy photon measured for a GRB and challenged existing ideas about production of the gamma-ray emission. Sylvain Guiriec modeled spectral properties of GRBs in Fermi's Gamma-ray Burst Monitor (GBM), finding a strong photospheric component in the short GRB 1202323A. Brad Cenko has been using ground-based optical telescopes to find counterparts of GRBs seen with the GBM. GRBs have not been the only transient puzzle. The LAT also captured outbursts from two classical novae in 2013, bringing the total observed with the LAT to five and deepening the mystery of what drives gamma-ray production in novae. While other efforts have focused on the foreground sources of gamma rays, Venters has been working on decoding signatures in the gamma-ray background connected to the intergalactic magnetic field strength. A busy year of milestones, gamma-ray catalogs, and new and unexpected discoveries closed with the transition of the Fermi all-sky survey to a new observation strategy that maximizes exposure toward the Galactic center, a region dense in gamma-ray activity and of particular interest for searching for dark matter signatures and possible high-energy flaring as the G2 cloud passes near the central black hole.

## Swift

Swift is a NASA Explorer mission, with international participation, that is designed to find gamma-ray bursts and other transients and study them over a wide range of wavelengths, from gamma rays to optical light. It was launched in 2004 and is in its extended mission phase with re-entry no earlier than 2025. There are three telescopes aboard Swift: the Burst Alert Telescope is a coded-aperture hard X-ray detector that operates between 15 and 150 keV; the X-Ray Telescope observes in the 0.2–10 keV energy band; the UltraViolet/Optical Telescope collects data between 1600 and 6000 angstroms.

In nine years since launch, Swift has detected and localized more than 800 GRBs. Some of the mission's most recent key scientific accomplishments have been:

- Discovering the first short hard burst (GRB 130603B) associated with a “kilonova.” These observations provided strong support for the theory that short bursts are due to the merging of binary neutron stars.
- Making high-quality metallicity measurements of star-forming regions at the highest redshifts ( $z > 5$ ) using GRBs (e.g., GRB 130606A at  $z=5.9$ ).

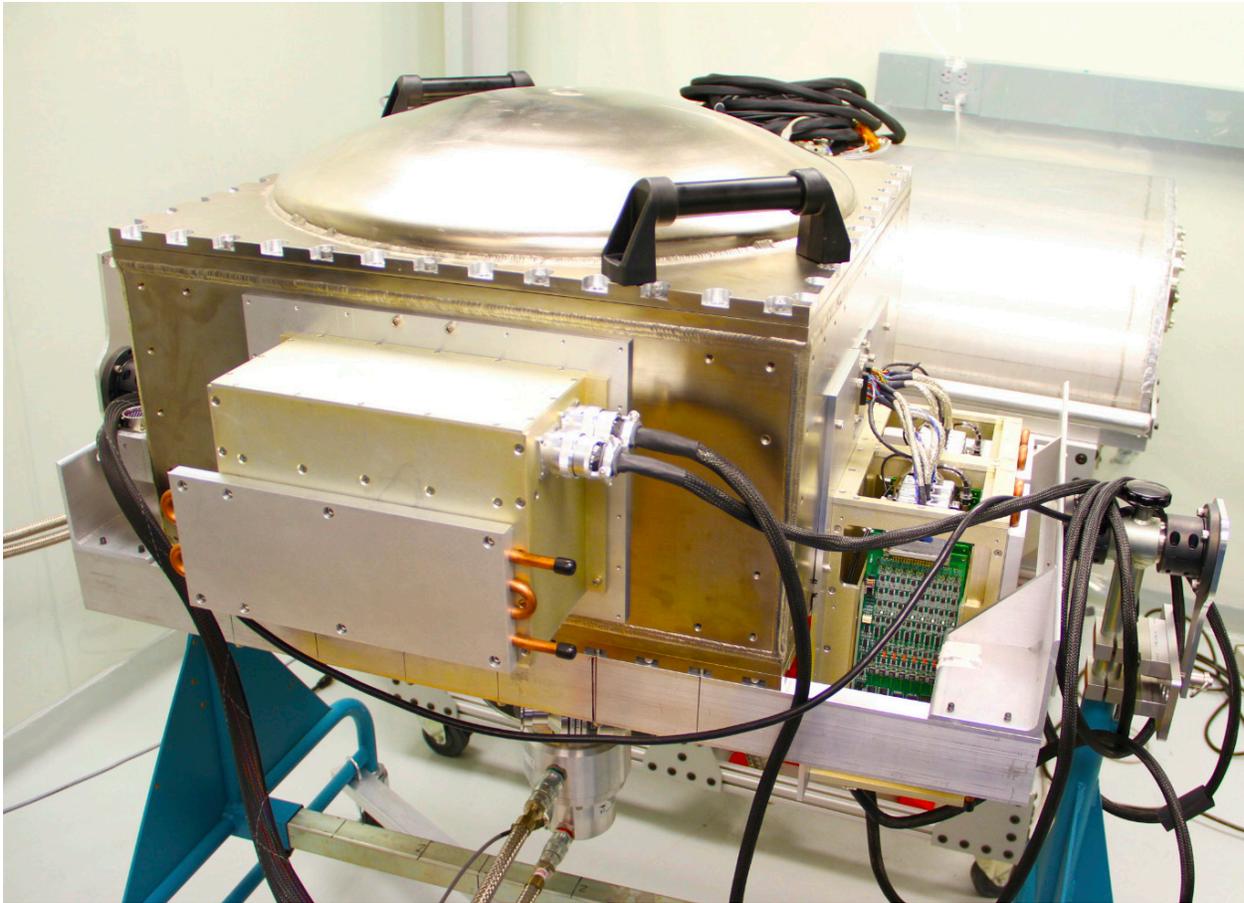
- Discovering new types of transients, such as ultralong GRBs, relativistic tidal disruption events, and supernova shock breakouts, and extreme stellar explosions, such as the record-setting GRB 130427A.
  - Discovering the first pulsar anti-glitch in the magnetar 1E2259+586 in the RCW103 supernova remnant. These observations call for a rethinking of glitch theory for all neutron stars. Discovering a new magnetar in the Galactic center, SGR J1745–29, located just arcseconds from SGR A\*.
- Swift has been widely recognized as a ground-breaking mission. It was ranked first in the 2012 Senior Review. By the end of 2013, nearly 2,000 refereed papers have been published that are based on Swift results, with 40 discovery papers in either Nature or Science (six in 2013).

The Swift Guest Investigator Program adds an important peer-reviewed component to the Swift research and includes both GRB and non-GRB science. During the 2013 Cycle 10, 175 proposals were received, requesting \$5.3M in funds and 15.6 Ms total exposure time for 1,150 targets. The oversubscription rate is a factor of 4.4.

Goddard scientists involved in Swift are L. Angelini, S. Barthelmy (PS), W. Baumgartner, P.



*ASD outreach: Wayne Baumgartner took this beautiful photo of Comet Pan-STARRS (C/2011 L4) and the Washington monuments from the West Front of the U.S. Capitol on March 12, 2013.*



*The RIMAS dewar assembled in the lab with the detector readout electronics attached.*

Boyd, J. Camp, J. Cannizzo, B. Cenko (DPS), T. Cline, J. Cummings, N. Gehrels (PI), H. Krimm, A. Lien, C. Markwardt, F. Marshall, J. Racusin, A. Smale, and E. Troja.

## MISSION AND INSTRUMENT CONCEPTS

### RATIR and RIMAS

The Reionization And Transients InfraRed (RATIR) camera has been successfully operating at San Pedro Martir observatory of the Universidad Nacional Autónoma de México (UNAM) in Baja California. The instrument follows up Swift GRB triggers in an automated mode. Since the beginning of its operation in December 2011, RATIR has followed up 59 events, producing photometry in the visible and infrared bands. The project is a collaboration between Goddard (N. Gehrels, A. Kutyrev, H. Moseley, E. Troja), UC Berkeley, ASU (PI, N. Butler) and UNAM. The agreement to continue the operation of

the instrument has been extended for another two-year period.

RIMAS (Rapid IMager-Spectrometer) is a joint project with the University of Maryland to develop an instrument for the Discovery Channel Telescope (DCT) at Lowell Observatory in Flagstaff. Goddard scientists are A. Kutyrev, B. Cenko, N. Gehrels, H. Moseley. RIMAS will have imaging and spectroscopic capabilities in the infrared region from  $0.95\mu\text{m}$  to  $2.4\mu\text{m}$ . It will be used to follow up transient sources, including gamma-ray bursts and supernovae. The instrument is currently under construction. As part of the collaboration with Lowell Observatory, initial observations of GRB afterglows have been carried out with the existing DCT visible imaging camera.

### ISS-Lobster

ISS-Lobster is a wide-field X-ray transient all-sky monitor proposed for deployment on the International Space Station. It represents a collaboration of scientists from across the Division, includ-



*BESS-Polar II prepares for launch from Williams Field near McMurdo Station, Antarctica, in December 2007.*

ing 661 personnel. We report on this mission concept in the [Gravitational Wave Astrophysics Laboratory \(663\) section](#).

### **Wide Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA)**

WFIRST-AFTA is a concept currently being studied as an astrophysics mission for the 2020s.

Lab chief Neil Gehrels is the Project Scientist and both Gehrels and Brad Cenko provide support for the mission study, on which we report in the [Exoplanet Laboratory \(667\) section](#).

## **SUBORBITAL**

### **Balloon-Borne Experiment with a Superconducting Spectrometer - Polar (BESS-Polar)**

BESS-Polar was developed for sensitive investigations of the nature of the dark matter and the apparent dominance of matter over antimatter using long-duration balloon flights over Antarctica. The collaboration is co-lead by Goddard (J. Mitchell) and KEK (High Energy Accelerator Research Organization, A. Yamamoto) and ASD team

members are J. Mitchell, M. Sasaki, K. Sakai, and T. Hams.

BESS-Polar uses a thin solenoidal superconducting magnet with a drift-chamber tracking system providing a large geometric acceptance for rare-particle measurements. Detectors to measure the charge and velocity of incident particles, time-of-flight scintillators and an aerogel Cherenkov counter form partial cylinders around the magnet. A middle time-of-flight layer within the magnet, below the tracker, reduces the threshold energy to about 100 MeV referenced to the top of the atmosphere.

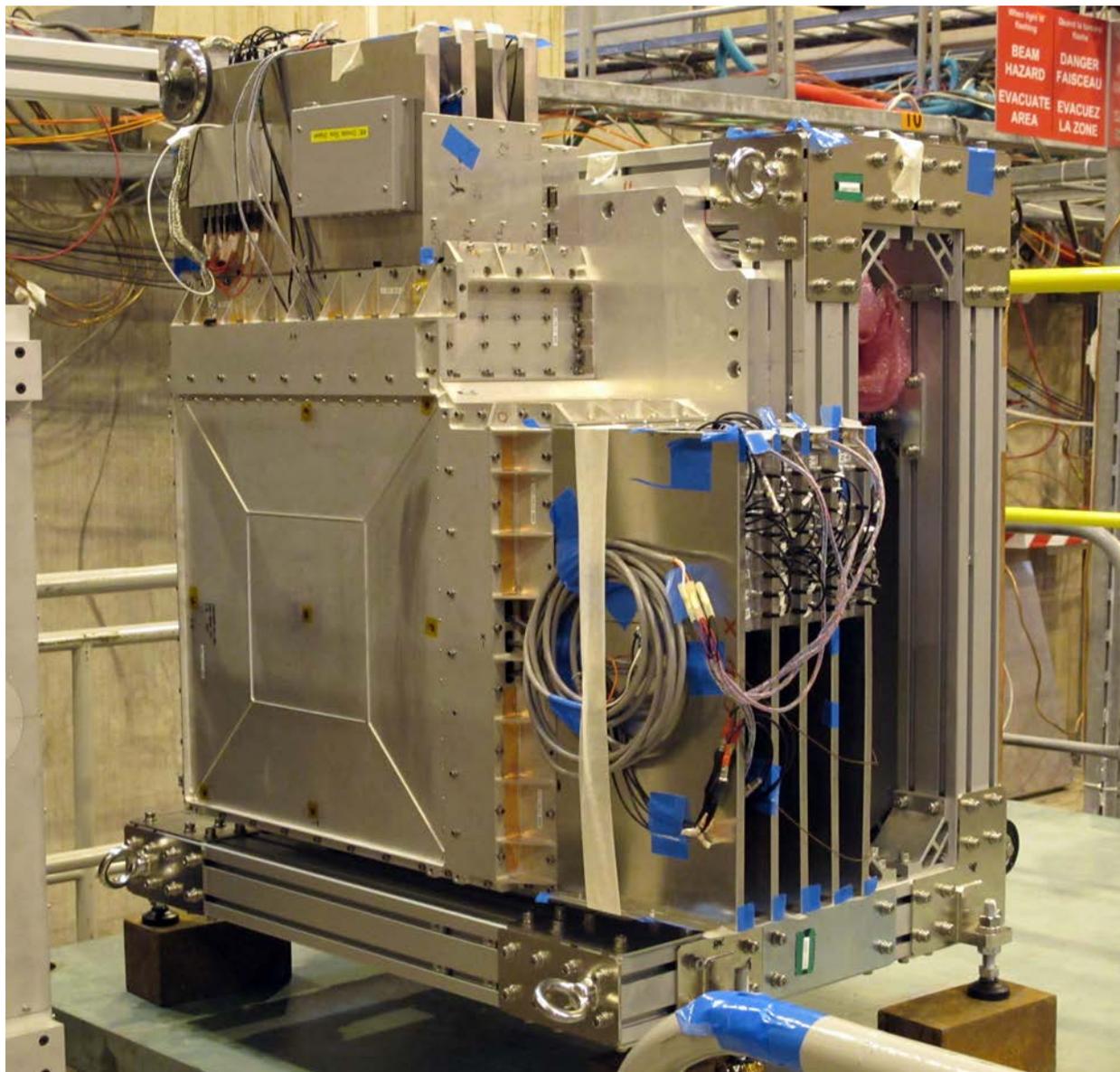
BESS-Polar has investigated the possibility that low-energy antiprotons might result from evaporation of small ( $\sim 5 \times 10^{11}$  kg) primordial black holes by Hawking radiation. BESS-Polar II identified 7,886 cosmic ray antiprotons between 0.17 and 3.5 GeV in 24.5 days of flight at solar minimum (2007–2008) when the signature of a primary source would be least affected by solar modulation. Within statistics, no evidence was found of primary antiprotons from primordial black holes. BESS-Polar II data were also carefully searched for evidence of antihelium. Combining all BESS-Polar and BESS data gave an upper limit to the ratio of antihelium to helium of  $6.9 \times 10^{-8}$ , the most stringent limit to date and stronger by more than three orders of magnitude than the first limits reported. Final analysis of high-precision BESS-Polar proton measurements is nearing completion. Preliminary results were presented at the

33rd International Cosmic Ray Conference in Rio de Janeiro in July 2013.

### Calorimetric Electron Telescope (CALET)

CALET is a new mission for the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS), manifested to fly on HTV-5 (H-II Transfer Vehicle 5) in 2015. CALET will measure the high-energy spectra of electrons, nuclei, and gamma-rays to investigate

signatures of dark matter, the sources of high-energy particles and photons, and the details of particle acceleration and transport in the galaxy. A 27-radiation-length deep-imaging particle calorimeter provides energy resolution of a few percent and excellent separation between hadrons and electrons and between charged particles and gamma rays. Plastic scintillators measure particle charge and act as anticoincidence detectors for gamma-ray measurements. CALET is a JAXA project (PI, S. Torii, Waseda University) with researchers from Japan, Italy, and the U.S. (Louisiana State University, Goddard, Washington University in St. Louis,



*The engineering model of the CALET Main Telescope during the 2012 beam test at the CERN SPS. The zenith surface of the detector is pointed to the left in this picture to accept the incoming particle beam.*



*The CREAM instrument during balloon inflation for an Antarctic flight.*

and the University of Denver). The ASD team of J. Mitchell, T. Hams, J. Krizmanic, A. Moiseev, and M. Sasaki are responsible for the instrument simulation, performance models, and accelerator testing and calibration. Krizmanic and Moiseev lead the U.S. simulation effort.

CALET is focused on investigating the high-energy total electron spectrum into the trans-TeV energy range. These measurements have the potential to identify, for the first time, the signature of high-energy particles accelerated in a local astrophysical engine and subsequently released into our galaxy. Because electrons lose energy rapidly by synchrotron and inverse Compton processes, TeV electrons must have been accelerated within about 100,000 years and can have diffused at most a few hundred parsecs. CALET will also search for signatures of dark-matter-annihilation in electron and gamma-ray spectra. Its measurements of cosmic ray nuclei from hydrogen to iron will extend into the region of the “knee” around of  $10^{15}$  eV to investigate possible structure and energy-dependent composi-

tion changes and to measure the ratio of secondary to primary cosmic rays. CALET will perform a gamma-ray all-sky survey, complementing Fermi and HESS observations, to detect intense high-energy sources, study the diffuse component, and search for new regions of emission. CALET includes a low-energy (7 keV–20 MeV) gamma-ray burst monitor. GRB measurements are extended to high energy using the calorimeter.

CALET has been tested at the CERN (European Organization for Nuclear Research) Super Proton Synchrotron (SPS) using proton and electron beams up to 400 GeV in energy and with heavy-ions from a fragmented Pb beam. Mitchell co-led these tests and carried out SPS beam tuning and development.

### **ISS Cosmic Ray Energetics and Mass (ISS-CREAM)**

The ISS-CREAM instrument is adapted from the balloon-borne CREAM payload and planned for

launch to the JEM-EF on ISS in 2015 using the SpaceX Dragon. ISS-CREAM will make direct measurements of cosmic-ray spectra from protons to iron to energies approaching the spectral “knee” around  $10^{15}$  eV. These measurements will test models of cosmic-ray acceleration and provide calibration data required to interpret ground-based air-shower measurements. In addition, ISS-CREAM measurements of the energy-dependent abundance ratios of secondary cosmic-ray species to their primary progenitors will test models of cosmic-ray transport and storage in the galaxy. ISS-CREAM will also measure cosmic-ray electrons into the TeV energy range to investigate possible contributions of local cosmic particle accelerators. ISS-CREAM uses a tungsten/scintillating-optical-fiber calorimeter to measure the energy of incident particles and silicon pixel detectors to measure particle charge. Scintillator-based detectors distinguish electron and hadron showers. The ISS-CREAM collaboration includes the University of Maryland (PI, Eun-Suk Seo), Goddard, Pennsylvania State University, and Northern Kentucky University, as well as collaborators in Korea, France, and Mexico. ASD team members are J. Mitchell and J. Link. Goddard, Penn State, and Northern Kentucky University are building a new Boronated Scintillator Detector for ISS-CREAM that measures neutrons to help distinguish high-energy electron cascades in the calorimeter from those initiated by protons. Because more neutrons are produced in hadronic cascades than in electromagnetic showers of the same energy, the neutron count is a sensitive discriminator to determine whether a shower was initiated by a hadron, such as a proton or atomic nucleus, or by an electron or gamma ray.



*The SuperTIGER-1 instrument before launch on Dec. 8, 2012, the start of a record-breaking 55-day flight.*

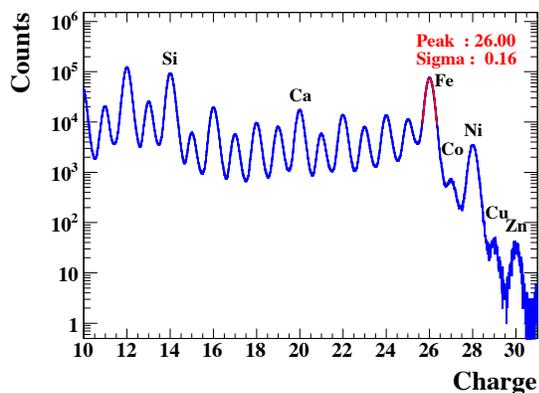
## Super Trans-Iron Galactic Element Recorder (Super-TIGER)

SuperTIGER, a new, large-area cosmic-ray instrument for long-duration Antarctic balloon flights, was launched on Dec. 8, 2012, from Williams Field, Antarctica. In about 2.7 circumnavigations of Antarctica, it flew for over 55 days, setting duration records for heavy-lift scientific balloons. The instrument returned excellent data on over  $50 \times 10^6$  cosmic-ray nuclei heavier than Ne. The SuperTIGER collaboration includes Washington University in St. Louis (PI, W. Robert Binns), Goddard, Caltech, and JPL. The Goddard team includes J. Mitchell, T. Hams, J. Link, M. Sakai, and T. Brandt.

SuperTIGER measures the abundances of individual elements from neon-10 to neodymium-60. High-statistic measurements from zinc-30 to molybdenum-42 will test and clarify the emerging model of cosmic-ray origin in OB associations and models for atomic processes by which nuclei are selected for acceleration. Super-TIGER also measures the energy spectra of the more abundant elements silicon-14 to nickel-28 at energies  $0.8 \leq E \leq 10$  GeV/nucleon to search for features that microquasars or



*SuperTIGER-1 climbing out just after launch.*



*SuperTIGER-1 histogram of cosmic-ray elements measured up to zinc, which highlights the instrument's excellent resolution of individual elements.*

other phenomena could superpose on the otherwise smooth energy spectra.

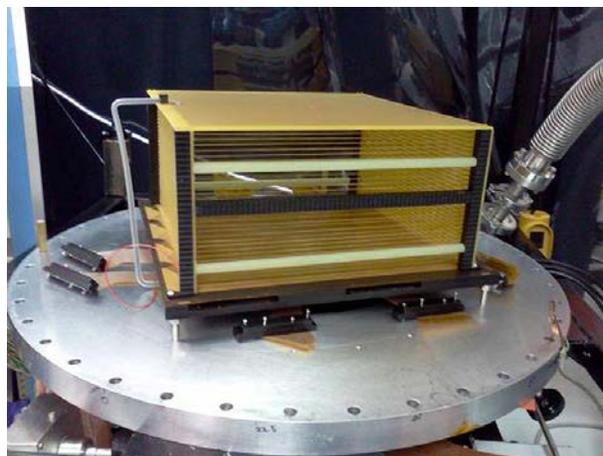
SuperTIGER uses three layers of plastic scintillator and two Cherenkov detectors, one with an acrylic radiator and one with a silica aerogel radiator, to determine the charge and energy of incident nuclei. A coded scintillating optical fiber hodoscope gives area and path length corrections. Two independent instrument modules, each with a  $1.16 \text{ m} \times 2.4 \text{ m}$  active area, give a total detection area of  $5.4 \text{ m}^2$  and an effective geometry factor of  $3.9 \text{ m}^2 \text{ sr}$  at selenium-34 after nuclear interaction losses are considered. Data from the SuperTIGER-1 flight show resolution at iron-26  $< 0.17$  charge units with clear peaks for every element up to molybdenum-42. Goddard is responsible for the scintillators, Cherenkov detectors, and instrument mechanical structure and has led the instrumental calibration and analysis effort.

Because the SuperTIGER-1 flight was terminated very late in the Antarctic season at a distance of 1,625 km from McMurdo, we were not able to recover it in 2013. However, photographs taken from an airplane show that the instrument is upside down with the detectors buried in the snow. Recovery is now planned for 2014/2015. A new SuperTIGER-2 instrument is planned for flight in 2017.

## TECHNOLOGY DEVELOPMENT

### Three-Dimensional Track Imager Detector for Gamma-ray Imaging with Polarization

Stanley Hunter, Seunghee Son, Michael Dion, and Andrei Hanu continued development of the Three-



$30 \times 30 \times 15 \text{ cm}^3$  3-DTI prototype; the  $30 \times 30 \text{ cm}^2$  MWD can be seen between the wires and supports forming the 15-cm tall drift volume. The flex-circuit connections between the MWD electrodes and the charge-sensitive front-end electronics have not been connected. The front-electronics and high-voltage supply for the drift grid are located below the aluminum plate.

Dimensional Track Imager (3-DTI) for a future gamma-ray telescope with the goal of providing optimum angular resolution and polarization sensitivity in the medium-energy (5–500 MeV) gamma-ray range. Dr. Hanu, a graduate of McMaster University and a NASA Postdoctoral Program Fellow, joined the 3-DTI development team in December.

The 3-DTI is a large-volume time-projection chamber (TPC) capable of three dimensional tracking and momentum measurements used for particle identification. A two-dimensional micro-well detector (MWD) serves as a spatial readout and multiplication stage while the third coordinate is obtained from the drift time of the primary charge through the gas volume. Each well of the MWD, 200 mm diameter on 400 mm centers, is an active gas proportional counter with gas gain of  $\sim 10^4$ . Negative ion drift is utilized to reduce the drift velocity and diffusion allowing for the large TPC volume.

Development of the 3-DTI technology this year has been slowed due to lack of limited funding. The team's accomplishments this year include:

- Teresa Sheets, with IRAD support, started development of multi-core processor hardware for parallel processing of the giga-bit per second streaming mode data expected from  $1 \text{ m}^3$  3-DTI modules. The goal of this effort is to define the high data rate processing equipment and parallel processing methods for handling the on-board, real time, memory intensive pro-

cessing of the Gb/s data stream to support the short-term and long-term development of the Advanced Energetic Pair Telescope (AdePT) instrument and other future scientific missions. A Tiler TILERcore-GX36-12 processor was purchased and existing code was ported to it and run. Streaming mode data including the cosmic ray background expected for the 3-DTI operating in low-Earth orbit has been simulated and tested with the Tiler hardware.

- An APRA proposal was submitted but not selected for continued funding. A new proposal will be submitted in FY14.
- A manuscript, “A Pair Production Telescope for Medium-Energy Gamma-Ray Polarimetry,” authored by S. Hunter, P. Bloser, G. Depaola, M. Dion, G. DeNolfo, M. Iparraguirre, J. Legere, M. McConnell, S. Nowicki, J. Ryan, S. Son, and F. Stecker, was submitted to Astroparticle Physics.

## AWARDS

In 2013, both the Columbia Scientific Balloon Facility in Palestine, Texas, and the SuperTIGER team won a NASA Honor Award for Group Achievement. Elizabeth Hays won the Robert H. Goddard Honor Award for Science for her “exceptional scientific performance in the discovery of high-energy gamma-ray flares from Galactic sources.”

## NEW FACES

### Brad Cenko



Brad earned his Ph.D. in 2008 from the California Institute of Technology. His thesis work, supervised by Profs. Fiona Harrison and Shri Kulkarni, studied the energetics and environments of Swift gamma-ray bursts. Following this, he served as a postdoc at the University of California, Berkeley, working with Profs. Alex Filippenko and Josh Bloom as part of the Palomar Transient Factory collaboration. In June, Brad arrived at Goddard as a new civil servant, where he will be working with the Swift and Fermi teams. His research interests are varied but largely fall under the rubric of observational time-domain astronomy,

including gamma-ray bursts, supernovae, and tidal disruption flares. Brad is also intent on developing instrumentation and software to enable novel observations of such time variable phenomena. He is excited about the opportunity to work with the extremely successful Swift team, in particular to help coordinate multiwavelength observations of the many exciting discoveries coming out of ground-based transient surveys.

### Antonino Cucchiara



In August, Antonio joined ASD as a NASA Postdoctoral Program (NPP) Fellow working on gamma-ray burst (GRB) science. Before that, he was a postdoc with a joint appointment at UC Berkeley and UC Santa Cruz working on GRB follow-up, spectroscopic studies of GRB afterglows and their host galaxies. He completed his Ph.D. at Penn State in the same topic. His interests include quasar absorption line studies and the chemistry of the early universe. He has become more involved in identifying and study the first stars and galaxies using GRB observations obtained with rapid spectroscopic follow-up campaigns, and he intends to get involved in developing a new generation of near-infrared instruments for ground-based telescopes and space observatories. He is excited to be at Goddard, reconnecting with old friends and co-workers from his early years in the U.S. (he is an Italian citizen) and at the same time learning very interesting aspects of the future space exploration. He is supplementing his ground-based expertise with knowledge acquired by working with missions like Fermi and Swift.

### Andrei Hanu



Andrei joined the ASD as an NPP Fellow in December to work on the AdePT Pair Telescope with Dr. Stanley Hunter. He received his doctorate in Medical Physics from McMaster University in Hamilton, Ontario, where he worked on the development of a THGEM (thick gaseous

electron multiplier) imaging detector. While he does not have a direct background in astronomy or astrophysics, he is interested in developing new gas-based, particle-tracker detectors, which have wide applications in astrophysics, nuclear physics, and medicine. He is particularly interested in the development of electron-tracking Compton cameras, which show tremendous potential to improve the spatial resolution and sensitivity of current PET and SPECT imaging devices. He came to Goddard to learn the techniques used in designing space instrumentation and to study how they can be applied to other fields in physics, particularly medical imaging devices. He is also looking forward to learning as much as he can about astrophysics while he is here.

**IN REMEMBRANCE**

*Dr. Jack Tueller (photo credit: Debbie McCallum/NASA / GSFC)*

Dr. Jack Tueller from the Astroparticle Physics Lab (661) in the Astrophysics Division passed away Feb. 20, 2013, after a battle with pancreatic cancer. Jack came to Goddard in 1979 after a Ph.D. with advisor Martin Israel at Washington University, St. Louis. He successfully flew his own cosmic ray thesis balloon instrument as a graduate student. At Goddard he pursued gamma-ray astronomy and became a world-renowned experimental astrophysicist. He worked with Bonnard Teegarden on the LEGS and GRIS balloon spectrometers and became the Principal Investigator for GRIS in 1993. GRIS was a highly successful payload with eight successful flights and scientific discoveries of gamma-ray line emission from SN 1987A and the distribution of positron annihilation line emission from the galactic center region. For these findings, he shared in the Lindsay Award in 1991. Jack was recently leading the InFOCuS balloon instrument for hard X-ray focusing science. He was the Project Scientist for NASA's balloon program. He was also highly active in the analysis of hard X-ray survey data from the BAT instrument on Swift. Jack was an ebullient and happy character who was the life of whatever activity he was involved with. Jack will be greatly missed by us all.

# X-ray Astrophysics Laboratory



Dr. Rob Petre  
*Lab Chief*



Dr. Joanne Hill  
*Associate Lab Chief*

## Laboratory Overview

The scientists in the X-ray Astrophysics Laboratory (Code 662) conduct investigations of a broad range of astronomical systems through the detection and analysis of their X-ray emission and other radiations they emit. Objects studied range from nearby solar system objects to cosmological structures. Researchers investigate the physics of extreme environments such as those near the event horizons of black holes and the evolution of stars, galaxies, and large-scale structures. The Laboratory is the preeminent developer of state-of-the-art X-ray astronomical detectors and optical systems for performing precise spectroscopy, polarimetry, timing, and imaging. These instruments have been employed in numerous suborbital applications (sounding rockets and balloons) and orbiting observatories. In addition to the civil service staff, the laboratory contains 65 university and contract scientists, engineers, technicians, post docs, and grad students.

## Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Megan Eckart	Low-temperature detectors, high-resolution X-ray spectroscopy, active galactic nuclei (AGN)	Astro-H SXS X-ray calorimeters	Calibration Scientist
Keith Gendreau	Pulsars, black holes, X-ray interferometry, diffractometers, cosmic X-ray background, X-ray spectroscopy	NICER Astro-H SXS	Principal Investigator Co-Investigator
Joe Hill-Kittle	X-ray polarimetry, X-ray detectors, gamma-ray bursts	Swift X-ray polarimeter	XRT Instrument Scientist
Ann Hornschemeier Cardiff	Accreting binary populations, starburst galaxies, AGN, clusters and groups of galaxies	Physics of the Cosmos Program Astro-H SXS NuSTAR ISS-Lobster	Chief Scientist Co-Investigator Science team member <i>Johns Hopkins University</i>
Keith Jahoda	X-ray polarimetry, diffuse X-ray background	X-ray polarimeter	
Tim Kallman	X-ray spectroscopy, polarimetry of accreting compact objects	Astro-H SXS	Co-Investigator
Richard Kelley	X-ray astrophysics, imaging X-ray spectroscopy using X-ray calorimeters.	Astro-H SXS	U.S. Principal Investigator

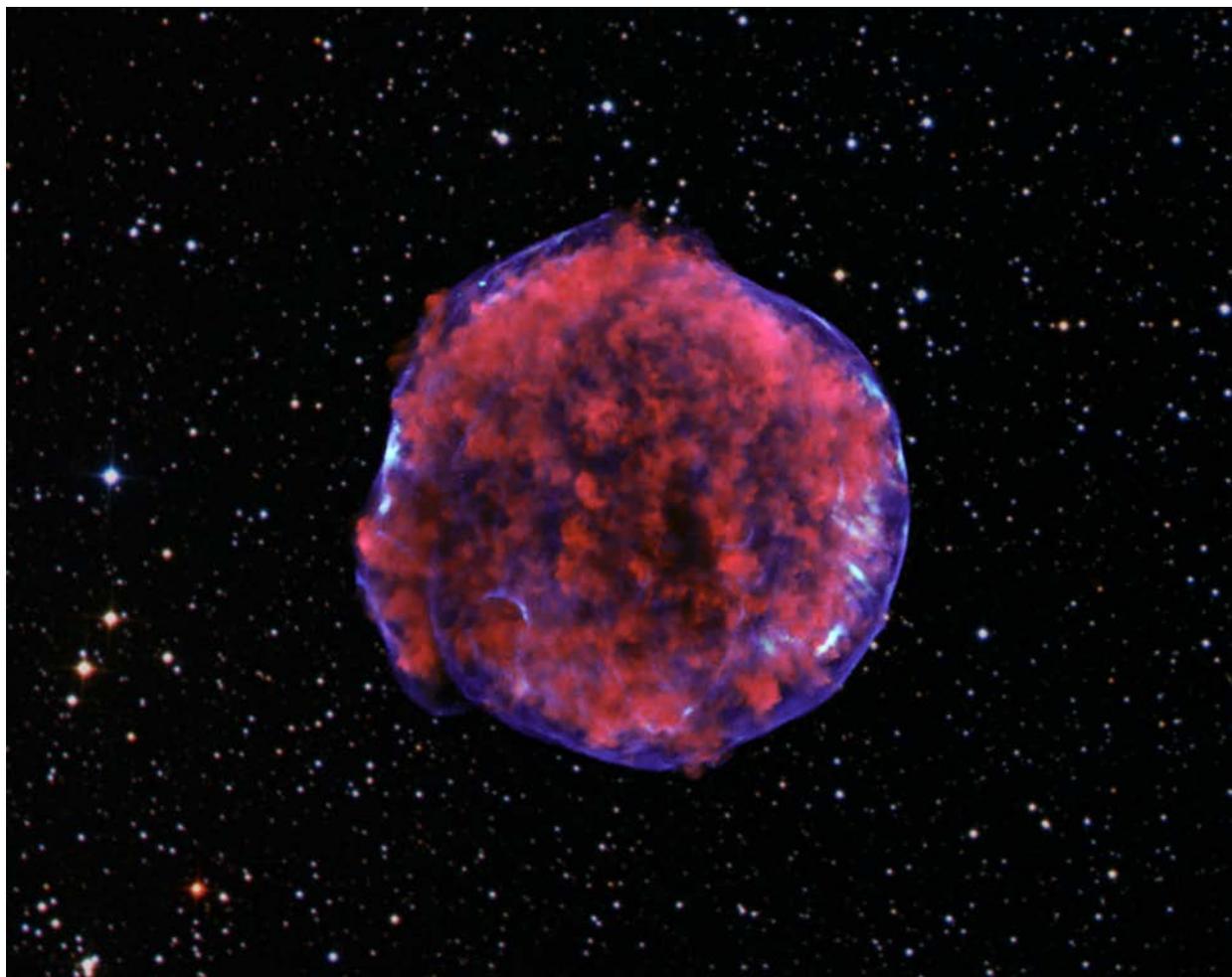
Scientist	Research Interest	Project/Mission	Role/Affiliation
Caroline Kilbourne	Low-temperature detectors, high-resolution X-ray spectroscopy, starburst galaxies, WHIM	Astro-H SXS X-ray calorimeters	Instrument Scientist
Maxim Markevitch	Clusters of galaxies, dark matter, X-ray imaging and spectroscopy, Sunyaev-Zeldovich effect	Astro-H	Science Advisor <i>JSI</i>
Craig Markwardt	X-ray binaries, X-ray polarimetry, pulsar timing, obscured AGN	NuSTAR Swift ISS-Lobster	Mission Scientist
Takashi Okajima	X-ray mirrors, AGN, galaxy clusters, CZT Detectors	Astro-H SXS  NICER InFOCuS	Soft X-ray Telescope Lead, Instrument Scientist X-ray Concentrator Lead
Rob Petre	X-ray studies of supernova remnants, supernovae, pulsar wind nebulae and young stars, X-ray optics	Astro-H SXS Suzaku ISS-Lobster	Co-I, U.S. Project Scientist U.S. Project Scientist
Andy Ptak	Starburst galaxies, obscured AGN, galaxy evolution, and scientific software development	WFIRST-AFTA NuSTAR ISS-Lobster	Study Scientist <i>Johns Hopkins University</i>
Scott Porter	Astrophysical instrumentation, Laboratory astrophysics, soft X-ray background, charge exchange	Astro-H SXS, Micro-X DXL NASA sounding rocket program	Instrument Scientist Institutional PI Institutional PI Deputy Project Scientist
Peter Serlemitsos	Low-energy electrons, X-ray spectroscopy, the X-ray background, SN remnants, clusters of galaxies	Astro-H SXS	Co-Investigator Soft X-ray Telescope lead
Steve Snowden	Diffuse X-ray emission from the Milky Way, local ISM and solar wind charge exchange emission from the heliosphere and Earth's magnetosheath	XMM-Newton	U.S. Project Scientist
Tod Strohmayer	Physics of compact objects	NICER ISS-Lobster	<i>JSI</i>
Jean Swank	X-ray polarimetry, black holes, neutron star pulsars		Emeritus
Kim Weaver	AGN, starburst galaxies, accretion disks, ultraluminous X-ray sources		<i>Johns Hopkins University</i>
Will Zhang	X-ray instrumentation, both optics and detectors, X-ray timing, compact objects, X-ray binaries	Lightweight and high-resolution X-ray optics, NuSTAR	SAT program PI

## SCIENCE HIGHLIGHTS

### The reverse shock of Tycho's SNR

Shock waves are ubiquitous phenomena observed not only in the Earth but also in Universe. Unlike

terrestrial shocks, astrophysical shock waves are likely mediated by something other than particle collisions, such as electromagnetic field, but how these shocks are formed has been one of the most important, long-standing questions in astrophysics. An ASD scientist, Dr. Hiroya Yamaguchi, studied



*An image of Tycho's supernova remnant taken by NASA's Chandra X-ray Observatory. Low-energy X-rays (red) show expanding supernova ejecta and high-energy X-rays (blue) reveal the blast wave, a shell of extremely energetic electrons. Credit: NASA/CXC/Rutgers/K. Eriksen et al. (X-ray) and DSS (optical)*

the reverse shock in Tycho's supernova remnant using the Suzaku X-ray satellite.

Tycho's supernova was witnessed by the famous astronomer Tycho Brahe in 1572, and its remnant is now glowing in X-rays. It had been believed that the remnant is brightened thanks to the reverse shock, which is the inward-moving sonic boom propagating into the supernova ejecta at Mach numbers of several thousand. This shock heats gases inside the remnant and causes them to fluoresce in much the same way as the gas in household fluorescent lights. Dr. Yamaguchi discovered the fluorescence emission, known as the K-beta line, from iron atoms that have just crossed the reverse shock front. The emission was faint but much more intense than expected. This indicates that the gases are rapidly heated by a process known as collisionless electron heating, where electrons crossing the shock become rapidly energized. Bright X-ray emission is dominated

by supernova ejecta heated by the reverse shocks through this process, which allows us to study in detail how the explosion occurred and how heavy elements were synthesized.

### **A new, young supernova remnant**

Led by Dr. Mark Reynolds of the University of Michigan, the Swift Galactic Plane Survey is mapping  $240 \text{ deg}^{-2}$  of the Galactic plane, from  $|l| \leq 60^\circ$  and  $|b| \leq 1^\circ$  through a series of brief exposures including simultaneous imaging at X-ray (0.5–10 keV) and ultraviolet (2000–2500 Å) wavelengths. One of the survey fields revealed a previously unknown extended X-ray source, which was not detected in the ultraviolet. The source has an angular extent of 4 arcminutes and a circular morphology with a partial shell, suggesting it is a Galactic supernova remnant



*A composite of newly discovered SNR G306.3–0.9. Blue represents X-rays from Chandra, red shows Spitzer infrared data, and radio observations from ATCA are purple. The remnant is about 4 arcminutes across. Credit: X-ray, NASA/CXC/Univ. of Michigan/M. Reynolds et al.; infrared, NASA/JPL-Caltech; radio, CSIRO/ATNF/ATCA*

(SNR), now designated G306.3–0.9. Subsequent investigation of archival Spitzer and radio data revealed an extended counterpart. The radio flux of the remnant is the lowest recorded for a Galactic SNR to date. As most SNRs are first identified through their radio emission, it is therefore no surprise that this remnant had escaped detection until now.

Follow-up Chandra and radio observations brought the object into better focus. The figure shows a composite image constructed using images from Chandra, Spitzer and Australia Telescope Compact Array. Chandra imaging reveals a complex morphology, dominated by a bright shock at the periphery. Spatially resolved X-ray spectroscopy using the Chandra data revealed properties consistent with an SNR approximately 2,500 years old, assuming a distance of 8 kpc. If this estimate is correct, then G306.3–0.9 is one of the 20 youngest Galactic SNRs. The Chandra spectra also revealed enhanced abundances of sulfur, argon and iron, indicating the presence of ejecta from the stellar explosion. On the other hand, there is no evidence for the presence of a compact stellar remnant.

### **Is NGC 253's supermassive black hole growing?**

Active star formation in the Sculptor galaxy, also known as NGC 253, is happening within 300 light-years of the galaxy's center, where a supermassive black hole (SMBH, about 5 million times the mass of the sun) also resides. Over the past 10 to 15 years, astronomers have shown that large bursts of star

formation are often accompanied by significant growth of the supermassive black holes at their galactic centers. Understanding the connection between star formation and supermassive black hole growth has been a major goal of astrophysics. As one of the nearest galaxies with starburst activity, NGC 253 offers a natural laboratory.

Thus far, it has been difficult to establish whether the supermassive black hole in NGC 253 is growing alongside the starburst. When black holes grow, they do so by accreting nearby gas. Before plunging into the black hole, the gas heats up to tens of millions of degrees and shines brightly in X-rays. For NGC 253, however, this process has been veiled by gas and dust along our line of sight. A Chandra observation in 2003 showed evidence of a bright X-ray source near the center of NGC 253, but it was not possible to determine if this was a growth signature from the supermassive black hole.

The higher energy X-ray emission probed by NuSTAR is less sensitive to obscuration by gas and dust and can clear up ambiguities present in previous X-ray observations. In a series of observations in 2012, we used the combined power of the NuSTAR and Chandra X-ray observatories to show unambiguously that the X-ray source from 2003 has turned off. Chandra pinpointed the location and NuSTAR demonstrated spectral signatures that are distinctly not from a SMBH. The supermassive black hole at the center of the galaxy is now effectively dormant and not growing much at all. Instead, the X-ray sources residing in the nuclear region include a new flaring ultraluminous X-ray source (ULX) and other powerful X-ray binary stars: these sources include

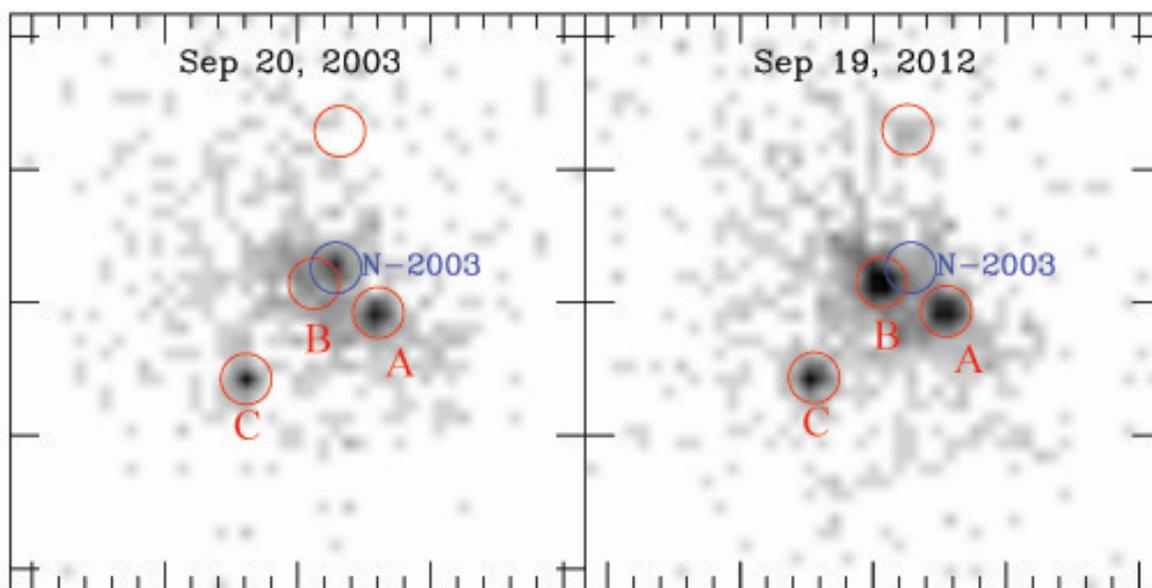


*This composite of the Sculptor galaxy merges NuSTAR X-ray observations (yellow and red blobs, 3– 20 keV) with a visible light image captured by the European Southern Observatory. The NuSTAR images are the sharpest ever taken of this galaxy in high-energy X-rays. Credit: NASA/JPL-Caltech/JHU*

either neutron stars or lower-mass (1 to 100 solar masses) black holes that feed off of normal companion stars. Thus the X-ray emission from this galaxy is not being powered by a supermassive black hole, which must be accreting at very low levels. It is possible that the current starburst behavior in the cen-

ter of NGC 253 will eventually be followed by explosive growth of the supermassive black hole.

The findings suggest that the supermassive black hole at the center of the Sculptor galaxy has become inactive sometime in the past decade. Future obser-



*Chandra (2–7 keV) images of the central  $400 \times 400 \text{ pc}^2$  of NGC 253 from 2003 (left) and 2012 (right). The best candidate for an accretion signal from the supermassive black hole, N-2003 (blue circle), was observed in 2003. This source was not active in 2012 when the galaxy was observed by NuSTAR. Instead, another new bright source (red circle) appeared, but this was shown to be a ULX. Credit: Bret Lehmer/JHU*

variations from both telescopes should help address this mystery.

## PROJECTS IN OPERATION

### Suzaku (Astro-E2)

Suzaku is the fifth in a series of Japanese X-ray astronomy satellites, launched by the JAXA on July 10, 2005. Like ASCA before it, Suzaku is a joint Japan-U.S. mission, developed by JAXA's Institute of Space and Astronautical Science (ISAS) in collaboration with Goddard and many other institutions.

Suzaku's operational scientific payload includes two co-aligned instruments. The X-ray Imaging Spectrometer (XIS) consists of four imaging CCD cameras (three working), sensitive in the 0.3–10.0 keV band, each located at the focal plane of a dedicated X-ray telescope (XRT). The second is a non-imaging, collimated Hard X-ray Detector (HXD) sensitive in the 10–600 keV band. The X-ray Spectrometer (XRS) stopped working shortly after launch as the result of a spacecraft design error.

The spacecraft continues to function well despite being beyond its nominal three-year lifetime. The power output of the solar panels has stabilized since experiencing a sudden drop in 2012 due to radiation damage. ISAS is cautiously optimistic that observations with Suzaku can continue for several more years.

After supplying key flight hardware (key components of the XRS, plus five XRTs), Goddard's current role is operating the U.S. Suzaku Data Center. The Data Center is responsible for maintaining the data processing pipeline; processing and archiving the full mission data set and distribution of data to U.S. Guest Observers (GO); development and maintenance of proposal and observation planning tools and documentation; maintaining the calibration database; supporting US proposal reviews; and assisting GOs in analyzing data. The data center staff consists of three full-time scientists (Koji Mukai, Kenji Hamaguchi, and Katja Pottschmidt) and one programmer, plus part-time support from HEASARC staff. Rob Petre is the NASA Project Scientist and Lorella Angelini is the Deputy Project Scientist.

U.S. observers have access to 50 percent of the observing time, as well as all archival data. In the ninth observing cycle (proposal due date: Nov. 16, 2013), a total of 50 U.S. proposals were submitted, a decline due to concerns over the longevity of Suzaku and the absence of dedicated GO funding.

Suzaku has produced an abundance of results from a wide variety of cosmic X-ray sources. Prominent recent examples are:

- Suzaku observations show that clusters of galaxies have the same metal content throughout their interiors. This requires that the metals were ejected from the component galaxies earlier in their history than previously thought.
- Observation of the Tycho supernova remnant has revealed that heating of material at the reverse shock occurs far more rapidly than can be accounted for by collisional heating, indicating that our understanding of shock processes in supernova remnant evolution is far from complete.
- Suzaku has provided spin measurements of 20 supermassive black holes. The distribution of spins can be used to characterize the role in black hole growth of accretion of surrounding gas or mergers between smaller black holes.

### Nuclear Spectroscopic Telescope Array (NuSTAR)

Launched in June 2012, NuSTAR is a Small Explorer mission designed to observe the X-ray sky in the 3–80 keV band with unprecedented combined image and spectral resolution. NuSTAR is led by Principal Investigator Fiona Harrison at Caltech, managed by JPL with oversight from the Explorer Program Office at Goddard, with new and previous Mission Scientists Craig Markwardt and William Zhang. Goddard contributed nearly 7,000 thin glass substrates, the foundation of the innovative multi-layer X-ray mirrors manufactured and tested by a team led by Zhang. While standard monolayer X-ray mirrors are not reflective above 10 keV, NuSTAR's multilayer mirrors have sensitivity up to 80 keV. NuSTAR's combination of X-ray collecting area (800 cm<sup>2</sup> at 10 keV), imaging resolution (58" half-power diameter), and broadband energy coverage enable the study of cyclotron lines from X-ray pulsars, detection of Compton reflection from accreting black holes, observation of nucleosynthesis in supernova remnants, and a deep hard-X-ray survey to find highly obscured sources not detectable in other wavelength bands.

In 2013, NuSTAR continued smooth science operations. NuSTAR team members have over 50 submitted and 25 accepted refereed papers. The team has completed three of its five Level 1 scientific requirements to study supernova nucleosynthesis, very high-energy gamma-ray sources and core collapse



*In April 2013, Swift's BAT was triggered by a flaring X-ray source at the galactic center. NuSTAR detected X-ray pulsations with a period of 3.76 seconds from the source, revealing it to be a highly magnetized pulsar, shown here in an artist's impression. Measurements of the pulsar imply the presence of a strong magnetic field near the supermassive black hole at the center of the Milky Way. The discovery of additional pulsars could allow mapping of the black hole's accretion region. Credit: MPIfR/Ralph Eatough*

supernova explosions. Required large area surveys are 65–85 percent complete, and are expected to be fully complete before October 2014. The NuSTAR science data archive opened to the public in August 2013. Goddard's HEASARC hosts the archive and distributes science data, software, documentation and proposal tools for observers. More than 300 observations are available for download. Preparations began for the Senior Review proposal and for a guest observer program, to be tentatively announced in summer 2014. Goddard scientists participating on the NuSTAR science team are Markwardt, Zhang, Ann Hornschemeier, Andrew Ptak, Bret Lehmer, Stacy Teng, and Jane Rigby.

### **XMM-Newton Guest Observer Facility**

ASD operates the U.S. XMM-Newton Guest Observer Facility (XMM GOF). XMM is an ESA X-ray astrophysics mission with some U.S. hardware and software contributions. ESA allocates resources to sup-

port European XMM users but looks to the GOF to provide support to the large U.S. astrophysics community. GOF activities include facilitating the submission of GO proposals to ESA, distributing proprietary data to U.S. PIs, maintaining the full public science archive, and supplying expertise, analysis software and documentation to U.S. scientists.

The GOF works in conjunction with the ASD GOFs of other high-energy astrophysics missions (e.g., Fermi, Swift, and Suzaku) to lower costs and to ensure consistency in the areas of the budget proposal process, FITS tools, database structure, web pages and archival data access. Cost savings are leveraged by sharing resources, techniques, expertise and reusing software. GOF activities cover a very wide range of endeavors in support of XMM. This year, the GOF's duties included: continuing to develop software for the analysis of extended sources; updating the Optical Monitor Catalog (OMCat); updating the popular ABC and D Guides with the new SAS releases; continuing development of Perl script "wrappers" to streamline data reduction for non-experts; continuing to maintain the XMM bib-

liography (now ~5,000 papers over the mission's lifetime); and continuing development of Trend-data tools.

The XMM GOF was successful in the 2012 Senior Review process with recommended continued funding for GOF operations through FY15. The GOF has submitted a proposal to the 2014 Senior Review for continued funding through 2016.

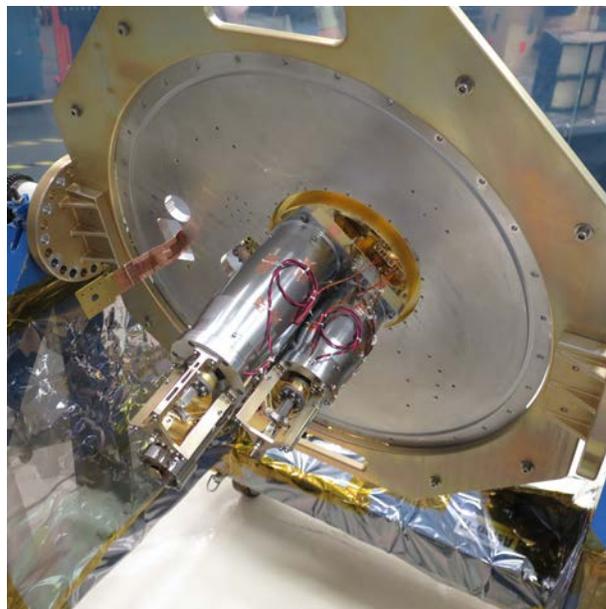
## PROJECTS IN DEVELOPMENT

### ASTRO-H

The X-ray Astrophysics Laboratory is collaborating with ISAS/JAXA to implement an X-ray calorimeter spectrometer for the Astro-H mission. The project, headed by Richard Kelley of the X-ray Astrophysics Laboratory, is implemented as an Explorer Program Mission of Opportunity to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments. Among laboratory scientists, Caroline Kilbourne and Scott Porter are responsible for the detector subsystem, and Peter Serlemitsos and his team of Takashi Okajima and Yang Soong are responsible for X-ray mirrors for both the SXS and the ISAS/JAXA Soft X-ray Imager (SXI). Megan Eckart and Maurice Leutenegger are developing the calibration program for the detector system. Prof. Dan McCammon of the University of Wisconsin, a long-term collaborator with the X-ray Astrophysics Laboratory and a pioneer in X-ray calorimeters, is developing a new generation of blocking filters for the instrument. Rob Petre is the U.S. Project Scientist for Astro-H.

The Astro-H Soft X-ray Spectrometer (SXS) will consist of a 36-pixel X-ray calorimeter array with better than 7-eV resolution to provide high-resolution X-ray spectroscopy over the 0.3–12 keV band with moderate imaging capability. The Goddard team is to provide the detector system, adiabatic demagnetization refrigerator (ADR, with a 50 mK operational temperature), electronics, blocking filters, and X-ray mirror, while ISAS/JAXA is responsible for the dewar system, other SXS electronics and the rest of the science payload, the spacecraft, launcher, and mission operations. The Space Research Organization of the Netherlands (SRON) is separately providing to JAXA a filter wheel and in-flight calibration sources.

The dewar will be a hybrid cryogen/mechanical cooler system for redundancy, and the X-ray mirror

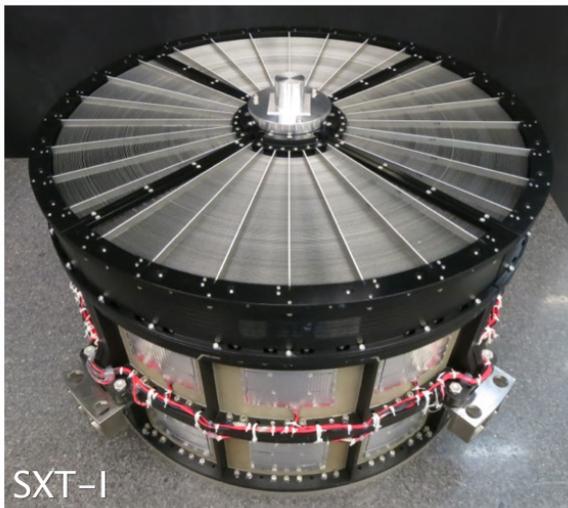


*The Astro-H Calorimeter Spectrometer Insert, which includes the calorimeter detector assembly and the three-stage adiabatic magnetic refrigerator system for cooling the array to 50 mK, was integrated in 2013.*

will build on the Goddard legacy of providing lightweight, high-throughput mirrors.

Astro-H is a facility mission to be launched on a JAXA H-IIA into low Earth orbit in late 2015. Its objectives are to trace the growth history of the largest structures in the universe, provide insights into the behavior of material in extreme gravitational fields, determine the spin of black holes and the equation of state of neutron stars, trace shock-acceleration structures in clusters of galaxies and supernova remnants, and to investigate the detailed physics of jets. Achieving these objectives requires the SXS and three additional scientific instruments to provide a very broad, simultaneous energy bandpass. The Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5–80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends the Astro H energy band to 600 keV, and the Soft X-ray Imager (SXI) expands the field of view with a new-generation CCD camera.

The SXS science investigation comprises building and delivering the SXS instrumentation and carrying out a six-month observing program in collaboration with ISAS/JAXA. The baseline mission includes two years of funding for the SXS science team and support for processing and archiving the SXS data for a total of three years. An approved Science Enhancement Option (SEO) will provide the U.S. community with access to Astro-H beyond



SXT-I



SXT-S

*Astro-H has two identical Soft X-ray Telescopes, SXT-I and SXT-S. Both mirrors exceed their requirements for collecting area and imaging performance.*

the baseline program. Under the SEO, U.S. scientists will be able to propose for Astro-H observing time and obtain grant support.

Working collaboratively with JAXA, the U.S. Guest Observer Facility will process, distribute, and archive data from all four Astro-H instruments, and provide observers with analysis tools and support. Lorella Angelini is leading the design and development of this program.

Numerous major activities and milestones have been accomplished this year. Foremost among these are the delivery of major flight hardware components to Japan, including the second of the two Soft X-Ray Telescope (SXT) mirror assemblies, and the Calorimeter Spectrometer Insert (CSI) that consists of the calorimeter detector assembly and the three-stage adiabatic magnetic refrigerator system for cooling the array to 50 mK. The detector subsystem was completed last year by Porter, Kilbourne, Meng Chiao, and Tomomi Watanabe, and, following extensive calibration spearheaded by Eckart and Leutenegger, was integrated with the ADR system to form the CSI in November 2013.

The flight aperture assembly (ApA) is nearing completion and will be taken to Japan in June 2014. This subsystem consists of many components, including a set of four blocking filters and filter mounts. These have gone through a variety of thermal cycles, and performance and vibration tests. Kilbourne and Sam Moseley have carried out these activities along with John Kazeva of the Applied Engineering and Technology Directorate, with assistance from Joe Adams.

The completed SXS instrument will begin extensive testing starting in about July 2014 and is scheduled for delivery to the spacecraft system in December.

During the past year, the Goddard Astro-H team, supported a variety of tests using the engineering version of the SXS. An end-end compatibility test will be carried out with all of the NASA and JAXA components of the instrument in January 2014 to demonstrate that the SXS is capable of < 5 eV energy resolution and that all of the NASA-JAXA electrical systems and communications function properly. The instrument will be going through further tests at the spacecraft level in the spring.

The second of two flight X-ray mirrors was completed by Serlemitsos, Takashi Okajima, and Soong and delivered to Japan in November 2013. Both X-ray mirrors exceeded their requirements for collecting area and imaging performance. In particular, the point spread functions of both mirrors is 1.2 arcmin, which is a significant improvement over the  $\sim 2$  arcmin of the Suzaku mirrors.

The Astro-H Science Enhancement Option has been approved by NASA/HQ and includes activities related to data analysis, the Guest Observer (GO) program and user support. To manage and implement these activities, Lorella Angelini has established an Astro-H U.S. data center at Goddard that is working closely with Japan. The pre-launch operations, rapidly ramping up, are focused on data processing, instrument software, collection of calibration information and preparing the necessary documentation and simulation software to support the GO program

for all four Astro-H instruments. The Astro-H U.S. data center will be the liaison between GOs and the Astro-H program, with a help desk that will open at times near launch. Mike Loewenstein and Hans Krimm joined this activity this year and are supporting the Soft X-Ray Spectrometer and Soft X-Ray Imager instruments, respectively.

## Neutron Star Interior Composition Explorer (NICER)

An Explorer Mission of Opportunity (PI: Keith Gendreau), NICER is an International Space Station (ISS) payload devoted to the study of neutron stars through soft X-ray timing. Neutron stars are unique environments in which all four fundamental forces of nature are simultaneously important. They squeeze more than 1.4 solar masses into a city-size volume, giving rise to the highest stable densities known anywhere. The nature of matter under these conditions is a decades-old unsolved problem, one most directly addressed with measurements of the masses and, especially, radii of neutron stars to high precision (i.e., better than 10 percent uncertainty). With few such constraints forthcoming from observations, theory has advanced a host of models to describe the physics governing neutron star interiors.

By answering a long-standing astrophysics question—How big is a neutron star?—NICER will confront nuclear physics theory with unique measurements, exploring the exotic states of matter within neutron stars through rotation-resolved X-ray spectroscopy. The capabilities that NICER brings to this investigation are unique: simultaneous fast timing and spectroscopy, with low background and high throughput. NICER will also provide continuity in X-ray-timing astrophysics more broadly, post-Rosati X-ray Timing Explorer (RXTE), through a proposed Guest Observer program. Finally, in addition to its science goals, NICER will enable the first space demonstration of pulsar-based navigation of spacecraft, through the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) enhancement to the mission, funded by the Space Technology Mission Directorate's Game-Changing Development program.

NICER's X-ray Timing Instrument (XTI) represents an innovative configuration of high-heritage components. The heart of the instrument is an aligned collection of 56 X-ray "concentrator" optics (XRC) and silicon drift detector (SDD) pairs. Each XRC collects X-rays over a large geometric area from a  $\sim 30$  arcmin<sup>2</sup> region of the sky and focuses

them onto a small SDD. The SDD detects individual photons, recording their energies with good ( $\sim 3$  percent) spectral resolution and their detection times to an unprecedented 100 nanoseconds RMS relative to Universal Time. Together, this assemblage provides a high signal-to-noise-ratio photon-counting capability within the 0.2–12 keV X-ray band, perfectly matched to the typical spectra of neutron stars as well as a broad collection of other astrophysical sources.

From NICER's ISS platform, a star-tracker-based pointing system allows the XTI to point to and track celestial targets over nearly a full hemisphere. The pointing system design accommodates the ISS vibration and contamination environments, and enables (together with NICER's GPS-based absolute timing) high-precision pulsar light-curve measurements through ultra-deep exposures spanning the 18-month mission lifetime. Anticipated launch of NICER is in late 2016, and additional information is available via the HEASARC (<http://heasarc.gsfc.nasa.gov/docs/nicer>).

NICER was first proposed in February 2011 and selected into Phase A in September 2011. A Concept Study Report was submitted to the NASA Explorers program in September 2012. On Jan. 29, 2013, the NICER team hosted the Explorer review panel at Goddard for a site visit. NICER was selected in Phase B on April 5. During September and October, the NICER development team held a series of Engineering Peer Reviews and, in December, NICER passed its Preliminary Design Review. The mission team includes MIT (detectors) and commercial partners providing flight hardware; the Naval Research Laboratory and universities across the U.S., as well as in Canada and Mexico, are providing additional science expertise.

## MISSION AND INSTRUMENT CONCEPTS

### ISS-Lobster

ISS-Lobster is a wide-field X-ray transient all-sky monitor proposed for deployment on the International Space Station. It represents a collaboration of scientists from across the Division, including 662 personnel. The emerging lobster-eye technology already is used in the DXL instrument launched on suborbital flights. We report on this mission concept in the **Gravitational Wave Astrophysics Laboratory (663) section**.

## SOUNDING ROCKET PROGRAM

### Diffuse X-ray Emission from the Local Galaxy (DXL)

The project uses an old payload repurposed for new science. It is now widely believed that a significant component of the soft X-ray background results from the interaction of the solar wind with neutral atoms within our solar system. Observing from low Earth orbit, we have seen significant emission from the solar wind interacting with exospheric neutral hydrogen (magnetospheric emission), and also the solar wind interacting with interplanetary hydrogen and helium (heliospheric emission). These two sources have very different spatial and temporal signatures, but are both the result of charge exchange recombination, where a highly ionized solar wind ion removes an electron from a neutral species, emitting photons, including X-rays, as it relaxes to its ground state. The DXL payload contains two 800 cm<sup>2</sup> proportional counters built in the late 1970s at the University of Wisconsin to map the soft X-ray background. However, DXL will use the same large-grasp instrument to spatially disentangle the heliospheric from the magnetospheric charge exchange emission and compare the results to modern spatial and temporal models of solar wind charge exchange.

The DXL project brings together scientists from several disparate fields. ASD scientists include Porter, Snowden, Kuntz, Chiao, and Thomas who have a strong interest in the soft X-ray background and in understanding the solar wind charge exchange contamination of many soft X-ray observations with ROSAT, Chandra, XMM, Suzaku, and soon, Astro-H. This is in partnership with Goddard collaborators Sibeck (674) and Collier (690) who study the interaction between the solar wind and Earth's exosphere to understand the critical boundary layer that drives much of space weather. The PI institution is the University of Miami, with the University of Kansas, the University of Wisconsin, and Leicester University as collaborating institutions.

The DXL payload also includes a Goddard-provided instrument, STORM, as a technology demonstration. STORM is a microchannel-plate X-ray detector with a wide field of view (10 × 10 degrees) lobster-eye slumped microchannel-plate optic. This is a prototype instrument for a full-scale magnetospheric charge exchange X-ray imager, and DXL is the first space-flight demonstration of this technology. The STORM instrument was developed at Goddard by ASD scientists Porter, Snowden,

Kuntz, Chiao, and Thomas with collaborators Collier (690), Sibeck (674), and the University of Leicester.

The DXL and STORM payloads successfully flew on Dec. 12, 2012. DXL clearly observed charge exchange from interplanetary helium in the helium focusing cone. STORM also clearly observed cosmic soft X-ray emission. Both instruments performed flawlessly and landed without damage. The next flight of DXL will add a third energy band proportional counter and is scheduled for mid-2015. A Cubesat version of STORM also will fly as a secondary payload as part of the mission.

### Micro-X

The Micro-X sounding rocket experiment is designed to be the first X-ray calorimeter payload using focusing X-ray optics. It uses significant design heritage from the XQC program, including a very similar adiabatic demagnetization refrigerator (ADR), however the detector and readout technology derive from the IXO program. The ASD research team include Porter, Kelley, Kilbourne, Bandler, Adams, Eckart, Smith, Serlemitsos, and Soong. Collaborating institutions include the University of Wisconsin at Madison, MIT, the University of Florida, and the National Institute of Standards and Technology (NIST). The Micro-X payload will use a 121-pixel (11 × 11) X-ray calorimeter array with superconducting transition edge (TES) thermistors operating at 50 mK. It is designed to have an energy resolution of 2 eV (FWHM) across the energy band from 0.05 to 2 keV. The Micro-X payload will use a focusing optic designed and produced at Goddard for the SXS sounding rocket that flew in 1989 and is the predecessor of the optics used for BBXRT, ASCA, Astro-E2, and Astro-H.

The Micro-X payload is scheduled to fly in late 2014 to observe the bright eastern knot of the Puppis A supernova remnant. The detector array is designed and produced at Goddard and will be read out using a cryogenic SQUID multiplexer and room-temperature electronics jointly developed by Goddard and NIST. Goddard has already provided the refurbished SXS X-ray optic with 200-cm<sup>2</sup> collecting area at 1 keV and a 2.5 arcmin PSF.

Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant, with about 40,000 counts expected during the flight. The payload will be the first opportunity to utilize high spectral resolution, broadband, spatial-spectral imaging and will provide a glimpse of what we

can expect from Astro-H and future larger-scale calorimeter instruments.

### Off-Plane Gratings Rocket Experiment (OGRE)

OGRE is an APRA-funded rocket flight expected to launch from Wallops in 2017. Its primary objective is to demonstrate key technologies necessary for a future X-ray observatory and provide the highest spectral resolution of  $E/\delta E \sim 2000$  between 0.2–1.3 keV. It is a collaborative effort of the University of Iowa (PI: Randall McEntaffer) and Goddard. It will integrate two key technologies already developed in a laboratory setting that have not been flight-proven. OGRE will use a slumped glass Wolter telescope, to be made by GSFC's Next Generation X-ray Optics team led by William Zhang (662), to provide excellent spatial resolution and increased throughput. A successful rocket flight will demonstrate its technical readiness, a requirement for flying this technology in future Explorer or major large X-ray missions. OGRE will also use radially grooved and blazed off-plane gratings to reduce grating aberrations and to focus the spectrum to one side of zero-order. Gratings of this type were invented in the 1980s and developed in the last decade but have not been flown. The spectrum will be focused onto a high spatial resolution CCD camera.

OGRE will produce the highest resolution spectrum of Capella to date. Capella is a binary system consisting of a G8 III giant and a G1 III giant. Strong coronal activity makes Capella one of the brightest X-ray sources in the sky. The emission-line-dominated spectrum often has been used as a calibration target and is included in the Chandra Emission line Project (<http://cxc.harvard.edu/elp/ELP.html>) with the goal of improving plasma spectral models with empirical line detections.

### X-ray Quantum Calorimeter (XQC)

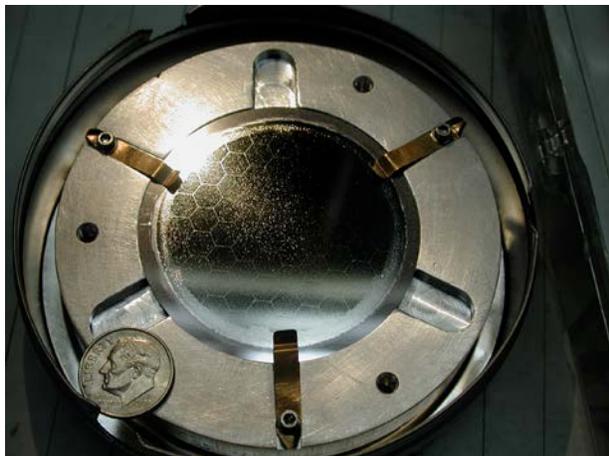
The X-ray Quantum Calorimeter (XQC) is a broadband non-dispersive X-ray spectrometer built to study the diffuse soft X-ray background (0.05–2 keV) from a sounding rocket. The instrument is designed to differentiate among the spectral components that are thought to make up the background, including emission from the Local Bubble, the Galactic halo, and solar wind charge exchange. The spectrometer utilizes a 36 pixel X-ray calorimeter

array with 8 eV FWHM energy resolution that was designed and produced at GSFC. The project is led by the University of Wisconsin, Madison. ASD research team members include graduate student Gabriele Betancourt-Martinez, scientist Meng Chiao, Eckart, Kelley, Kilbourne, and Porter.

The most recent launch of XQC occurred on Nov. 3, 2013. On the previous two flights the outer optical/IR blocking filter (at 130 K) acquired a thin layer of contamination after launch that significantly reduced the X-ray throughput of the instrument. For the 2013 flight, our collaborators at University of Wisconsin added an additional optical/IR blocking filter to the dewar system. This room-temperature filter was designed to eliminate in-flight contamination, and it worked perfectly. The X-ray transmission was as expected across the science bandpass. However, an instability in the second-stage Black Brant motor resulted in launch vibrations an order of magnitude higher than expected. This extra vibrational heating prevented the detector stage from reaching the planned operating temperature of 50 mK during the science acquisition; rather, the mi-



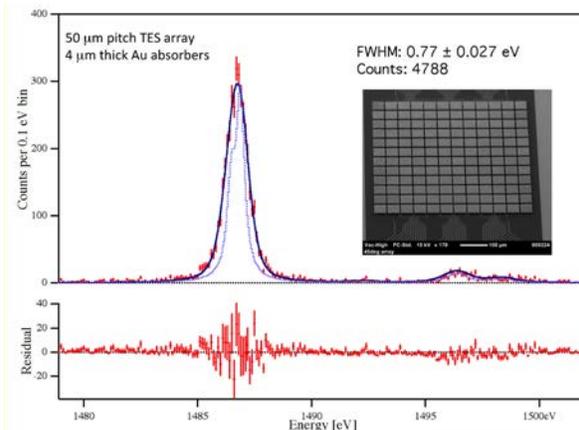
*XQC team members following vertical system tests on Nov. 2, 2013, the day before the experiment's launch.*



An optical/infrared blocking filter composed of a 70nm-thick film supported by a micromachined silicon mesh, shown here within its aluminum shipping fixture. This filter was incorporated into the outer room-temperature stage of the XQC dewar and successfully eliminated in-flight contamination of the cold dewar filters that limited the scientific return of the previous flight.

calorimeter array drifted from 60 mK to 52 mK over the course of the observation, causing a large drift in the energy gain scale. The payload was recovered safely, enabling acquisition of extensive post-flight calibration data over this range of detector operating temperatures. The team is presently developing a gain-scale reconstruction algorithm. Chiao and Betancourt-Martinez traveled to White Sands to assist in the 2013 launch campaign. Civil servant participation in pre-launch field work was minimal owing to the government shutdown. The next launch of XQC has yet to be scheduled, but it will be part of the planned sounding rocket campaign in Woomera, Australia.

In parallel, members of the Goddard X-ray microcalorimeter group in Codes 662 and 553 have worked extensively with University of Wisconsin graduate student Kelsey Morgan on her NASA Space Technology Research Fellowship (NSTRF) project to develop a next-generation detector array for the XQC payload. The proposed large-area TES microcalorimeters will achieve  $\sim 2$  eV FWHM energy resolution to enable measurements of the 0.25 keV diffuse X-ray background. This waveband is essential for studying the roles of solar wind charge exchange vs. thermal emission and the 8 eV FWHM resolution of the current-generation XQC array is inadequate to resolve the majority of the emission lines in this crowded region. In 2013, Morgan performed device design simulations and began mask layout



The spectrum of 1.5 keV aluminum  $K\alpha$  X-rays. The pixel dimensions are  $46 \mu\text{m} \times 46 \mu\text{m} \times 4 \mu\text{m}$ . The dotted line shows the intrinsic line shape of the  $K\alpha$  complex. The short lines represent the measured number of counts in each 0.1 eV bin and the error bar for each bin. The solid line is the intrinsic line shape convolved with the best fit instrumental broadening (assumed to be Gaussian). Inset: A scanning electron microscope image of a  $12 \times 12$  array of these pixels on a  $50 \mu\text{m}$  pitch.

for prototype TES microcalorimeters that have the potential to achieve sub-2 eV resolution with the required pixel area ( $\sim 900 \times 900$  microns).

## INSTRUMENTATION AND TECHNOLOGY DEVELOPMENT

### X-ray Calorimeter Development

An X-ray calorimeter determines the energy of an incident X-ray photon by measuring a small change in temperature. Three types of X-ray calorimeters presently dominate the field, each characterized by the thermometer technology. The first two types use temperature-sensitive resistors: semiconductors in the metal-insulator transition and superconductors operated in the superconducting-normal transition. The third type uses a magnetic thermometer. Goddard Space Flight Center is the only institution playing a leading role in the development of each of the three dominant X-ray calorimeter technologies. The scientists of the ASD microcalorimeter development team include Chiao, Eckart, Kelley, Kilbourne, Porter, Joe Adams, Simon Bandler, Fred Finkbeiner, and Steve Smith, along with postdoc Sang-Jun Lee and graduate student Betancourt-Martinez. Progress is made possible through a strong collaboration with James Chervenak, John

Sadleir, and Edward Wassell of Goddard's Detector Systems Branch (553).

Most recent development activity is going into advancing various configurations of microcalorimeter arrays that incorporate a gold or gold/bismuth absorber with a superconducting transition-edge sensor (TES) made from a molybdenum/gold proximity-effect bilayer. An array of 46-micron pixels optimized for the highest soft X-ray resolution has demonstrated 0.77 eV FWHM at 1.5 keV. Other fine-pitch arrays have been optimized for high counting rate. The resolution at 6 keV of a device achieving 1.6 eV FWHM at low count rates only degraded to 2.3 eV for an input count rate of 100 cps, with a throughput of 99.6 percent. Recently, a resolution of 2.6 eV at 400 cps, 2.9 eV at 620 cps, and 3.6 eV at 860 cps have been demonstrated; a full analysis of the dead time is still in progress.

Recent Goddard TES calorimeter development has been enhanced by new understanding that many TES properties can be explained by considering these devices to be superconducting weak links, and details of the transition are influenced by the magnetic fields produced by the bias current.

Recent tests to exploit the self-fielding for magnetic feedback to increase the sensitivity of TES microcalorimeters have demonstrated dramatic sharpening of the resistive transition, and iterations to optimize this tuning are in progress.

### Laboratory Astrophysics Using an X-ray Microcalorimeter with an Electron Beam Ion Trap

Our laboratory astrophysics program is designed to simulate astrophysical plasmas in the laboratory in order to benchmark and provide guidance to the atomic codes that form the basis of the spectral synthesis models used in X-ray astrophysics. These models are used to relate spectra observed from an astrophysical object to conditions in the source, including temperature, ionization-equilibrium, composition, density, turbulence and bulk motion. This work is fundamentally important as high-resolution spectroscopy becomes the dominant tool in exploring the physics of X-ray-emitting objects.



*ASD outreach: The Blueshift social media team organized a visit by science educator and rapper Coma Niddy (Michael Wilson) and a production team from PBS Digital Studios to Goddard on Dec. 16, 2013. They filmed scenes for a video about black holes and public misconceptions about them.*

This has already started with the observation of bright point sources with the high-resolution dispersive spectrometers on Chandra and XMM-Newton. It will become critically important with the upcoming Astro-H and X-ray missions that follow. Our program is designed to validate and correct the accuracy of the spectral synthesis models in controlled ground-based experiments, giving us confidence that we have correctly ascribed observed spectral features to known conditions in the astrophysical source.

The basis of our program is a high-resolution non-dispersive X-ray calorimeter spectrometer, a suite of very-high-resolution dispersive spectrometers, and the Electron Beam Ion Trap (EBIT) plasma generator at the Lawrence Livermore National Laboratory (LLNL). ASD scientists include Porter, Kelley, Kilbourne, Adams, Smith, Leutenegger, and Betancourt-Martinez. Other collaborating institutions include Stanford University and NIST. The LLNL EBIT can produce nearly any plasma conditions, from low-charge states in light elements to bare uranium with electron beam energies of up to 200 keV. Nearly any charge state of any astrophysically interesting element can be produced, either as a pure charge state or in a Maxwellian distribution at known temperature.

Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and non-thermal distributions. Measurements are related back to theory, the results of atomic calculations, and to the standard X-ray spectral synthesis models used in X-ray astrophysics.

A key instrument in these measurements is a broadband high-resolution X-ray calorimeter instrument provided by Goddard beginning in 2000 and now on its third revision. This system has been operated almost continuously for the past 9.5 years. It has produced well over two dozen peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell iron and nickel, as well as charge-exchange measurements in sulfur, carbon, oxygen and iron. Many investigations are ongoing. Recent emphasis has been a detailed look at L-shell charge exchange, mostly with sulfur and iron, as a function of ionization state, a key component of magnetospheric charge exchange for which there exists no predictive theory. Magnetospheric and heliospheric charge exchange are key compo-

nents of spatially, spectrally, and temporally variable foreground emission which complicate observations of, for example, the soft X-ray background, warm-hot intergalactic medium, and clusters of galaxies. Charge exchange emission is also very diagnostic and if observed in a celestial source can provide key information on the composition, ionization state, and relative velocity of both the donor and acceptor species. Our laboratory investigation is unique in the world at providing the first controlled high-resolution spectra of charge exchange in astrophysical elements and is geared to provide information to guide the development of a predictive atomic theory, especially for the key L-shell emission which dominates local charge exchange.

Goddard first installed an X-ray calorimeter at the LLNL EBIT facility in the summer of 2000; the XRS/EBIT was based on the engineering-model detector system for the Astro-E observatory. The system was significantly upgraded using technology developed for Suzaku (Astro-E2) in 2003. A dedicated facility-class instrument designed for laboratory astrophysics from the ground up was installed in 2007. The current instrument, dubbed the EBIT Calorimeter Spectrometer (ECS), utilizes a 32-channel X-ray calorimeter array from the Astro-E2 program installed in a long-lifetime automated laboratory cryostat that enables continuous experiments for up to 70 hours with a two-hour recharge. The detector array is populated with 16 mid-band (0.05–12 keV) X-ray absorbers with 4.5 eV FWHM resolution at 6 keV, and 16 high-band (0.1–100 keV) X-ray absorbers with 30 eV FWHM at 60 keV.

In addition to operating the ECS, we recently (spring 2011 and spring 2012) refurbished the XRS/EBIT spectrometer to perform photoexcitation measurements at the SLAC Linac Coherent Light Source (LCLS). In this experiment we combined a portable EBIT, the XRS/EBIT spectrometer, and a monochromator with the LCLS light source to breed and observe X-ray emission from photoexcitation in highly charged ions.

We are currently designing and constructing the fourth-generation instrument that will be based on detector technology from the IXO/Athena development program. It will be installed in a completely automated cryogen-free cryostat. This fourth-generation instrument is dubbed the Transition-Edge Microcalorimeter Spectrometer (TEMS) and will be composed of a checkerboard hybrid of 128 low-band (0.05–1 keV) pixels with 0.8 eV resolution at 1 keV, and 128 mid-band (0.05–10 keV) pixels with 2.0 eV resolution at 6 keV. In addition, there will be a

64 channel high-band array (0.1–200 keV) with 30 eV resolution at 60 keV. The TEMS instrument will become the workhorse in our laboratory astrophysics program to ensure that our measurements and understanding of atomic processes are ready to interpret the spectra we will obtain with Astro-H and future observatories. TEMS will be installed at the EBIT facility in late 2014

## Next Generation X-ray Optics

The group, led by Dr. William Zhang, has demonstrated the construction of mirror modules that perform at 10 arcsecond levels and pass all necessary environmental tests, including vibration, acoustic, and thermal vacuum. They have continued their effort to improve the angular resolution, with a plan to demonstrate 5 arcsecond resolution by the end of 2015 and paving the way for achieving 1 arcsecond resolution by the end of this decade. The construction of a mirror module is a three step process: substrate fabrication, coating, and alignment and bonding. Each step is improved in parallel.

For substrate fabrication, they are changing the glass forming process from slumping onto a convex mandrel to slumping into a concave mandrel. The reversal of mandrel polarity means that the X-ray reflecting surface of the finished substrate is no longer in direct contact with the mandrel surface during forming, thereby reducing and possibly eliminating middle-spatial-frequency errors caused by imprinting. The downside of this new approach is that it imposes an additional thickness uniformity requirement on the glass sheets. Now that the slumping process is much better understood and has met the original objective of making 15 arcsecond substrates for the Constellation-X mission, a small added cost of processing commercially procured glass sheets to achieve uniformity is warranted. The group expects to be able to improve the substrate quality by a factor of 2, from 6 arcseconds to better than 3 by the end of 2015. Meanwhile, the researchers are also pursuing a novel approach of making mirror substrates by polishing and light-weighting single crystal silicon mirrors. This process has the potential of making diffraction-limited X-ray mirrors.

Over the last year, they conducted a number of mirror-coating experiments using both atomic layer deposition and the magnetron sputter processes. Those experiments showed that coating both sides of a substrate simultaneously does not result in zero distortion, as one would expect. There may be a number of reasons to explain those results, includ-

ing coating thickness variation. In the process of understanding those results, they found that a thermal annealing process can significantly reduce thin film stress, and thereby the distortion it causes. They are continuing the process of optimizing the coating and annealing parameters and hope to reduce the contribution of coating distortion to angular resolution to less than 1 arc-second.

The group continues to verify and perfect the entire process by constructing mirror modules that contain three co-aligned pairs of Wolter I mirrors. The complete end-to-end construction and testing process allow researchers to identify and address problems that may otherwise elude them during individual steps. They are well on their way toward making 5 arcsecond modules by the end of 2015, enabling several potential Explorer missions.

## X-ray Mission Studies

Scientists from the X-ray Astrophysics Laboratory engaged in studies related to future large X-ray missions in collaboration with the PCOS Program Office. During the first half of 2013, a team led by Petre and Ptak, and including Kilbourne, Bandler and Zhang, wrote a Technology Development Roadmap for a large X-ray observatory. This document describes the steps, timescale and funding needed to bring key instrument technologies needed for a large X-ray mission to maturity: X-ray optics, calorimeters and grating spectrometers. This document was submitted to NASA Headquarters in August 2013.

In September, NASA formed a Science and Technology Definition Team (STDT) chartered to study an X-ray Probe mission concept during the 2013–2015 time frame. The goal was to define a calorimeter-based X-ray observatory costing less than one billion dollars and to provide a mission concept to NASA HQ to be considered for a possible 2017 start. Hornschemeier was co-chair of the STDT, Petre the Study Scientist, and Ptak the Deputy Study Scientist. Over the two months of study activity (October–November 2013), the Study Team performed several trade studies to see how mirror design could affect mission cost. The studies started with the single instrument calorimeter mission from the 2012 X-ray Mission Concepts Study (N-CAL) and showed that a 50-percent reduction in either mirror area or focal length does not result in significant cost savings. It appears that there is a substantial entry-level cost for any large mission involving an X-ray calorimeter.

The study was terminated in late 2013 after ESA announced that its L2 mission (with nominal 2028 launch) would be an X-ray observatory with scientific objectives encompassing those of the X-ray Probe. NASA has shifted its focus on a future large X-ray mission to discussions with ESA about contributing to L2. Petre is serving as the study scientist for this activity.

## AWARDS

In 2013, Jean Swank was awarded the NASA Distinguished Service Medal, the agency's highest honor, those who display distinguished service, ability, or courage, and have personally made a contribution representing substantial progress to the NASA mission. The contribution must be so extraordinary that other forms of recognition would be inadequate.

In 2012, Tim Kallman received a Robert H. Goddard Honor Award for Scientific Achievement "for his outstanding performance as GEMS Project Scientist." The Gravity and Extreme Magnetism Small Explorer (GEMS) project was led by Swank.

## NEW FACES

### Raul Riveros



Raul joined ASD's X-ray Astrophysics Laboratory in January 2013 as an NPP Fellow working with Dr. Will Zhang. He obtained his Ph.D. in mechanical engineering from the University of Florida in August 2012 and continued on there for a semester-long postdoc appointment.

His background is in manufacturing science with emphasis on surface finishing processes. His research interests lie in optical and nontraditional manufacturing and the immense challenges of building sub-arcsecond-resolution X-ray optics. He is excited to have the opportunity to work on the development of manufacturing processes for segmented single crystal silicon X-ray mirrors for future X-ray telescope missions.

### Malachi Tatum



Malachi earned his Ph.D. at the University of Maryland, Baltimore County, where he studied the importance of the Compton-thick X-ray re-processor in active galactic nuclei. This work included modeling selected Seyfert galaxies using a Compton-thick accretion-disk wind and un-

derstanding the spectral properties of a hard-X-ray-selected sample in context of reflection-dominated and absorption-dominated models. Malachi joined ASD as an NPP Fellow in November 2013 under the supervision of Andy Ptak and is focused on using the hard X-ray bandpass as a proxy for understanding the underlying power law continuum of active galactic nuclei and exploring how Compton-thick absorption in the X-ray band affects the energy budget of these systems, both offering insight into the link between black hole mass and galactic bulge properties. He also has interest in the connection between starbursts and active galactic nuclei. Malachi is most excited to work with the NuSTAR science group and awaits the launch of Astro-H.



# Gravitational Astrophysics Laboratory



Dr. Robin T. Stebbins  
*Lab Chief*

## Laboratory Overview

The Gravitational Astrophysics Laboratory (Code 663) conducts a broad range of scientific investigations into astrophysical regimes dominated by extreme gravity. The laboratory provides the scientific and technical leadership to develop space-based gravitational wave observatories and includes a mix of theorists and experimentalists. Research encompasses a variety of areas, including numerical relativity, gravitational-wave sources and data analysis, mission formulation, theoretical modeling of high energy astrophysical sources, and precision metrology. In addition to the civil servant staff, the laboratory has nine university scientists and postdocs.

## Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
John Baker	Gravitational wave astrophysics, numerical relativity, data analysis, GRMHD	WFIRST-AFTA eLISA	Study Scientist <i>JSI</i>
Jordan Camp	Multiwavelength astronomy, precision measurement	LIGO, eLISA, ISS-Lobster	<i>LSC</i>
Alice Harding	Pulsars, gamma-ray emission	Fermi, NICER	<i>JSI</i>
Demos Kazanas	Black holes, compact objects, active galactic nuclei, gravitation		
Jeff Livas	Gravitational wave astrophysics, precision measurement, laser communications, small satellites	eLISA	
Jeremy Schnittman	Black holes, X-ray polarization, gravitational wave astrophysics, exoplanet atmospheres	eLISA, Lobster, ATLAST	<i>JSI</i> <i>John Hopkins University</i>
Robin Stebbins	Gravitational wave astrophysics, precision measurement	eLISA GRACE Follow-On	
Floyd Stecker	Cosmic gamma rays, gamma-ray astronomy, high-energy astrophysics, astrophysical tests of relativity	Fermi	<i>UCLA</i>
J. Ira Thorpe	Gravitational wave astrophysics, precision measurement	eLISA, LISA Pathfinder	LPF Science Team
Richard Fahey	Relativity	Emeritus	<i>U.S. Naval Academy</i>
Vigdor Teplitz	Relativity, exotic particles	Emeritus	<i>U.S. Department of State</i>

## SCIENCE HIGHLIGHTS

### How Black Holes Shine in Hard X-rays

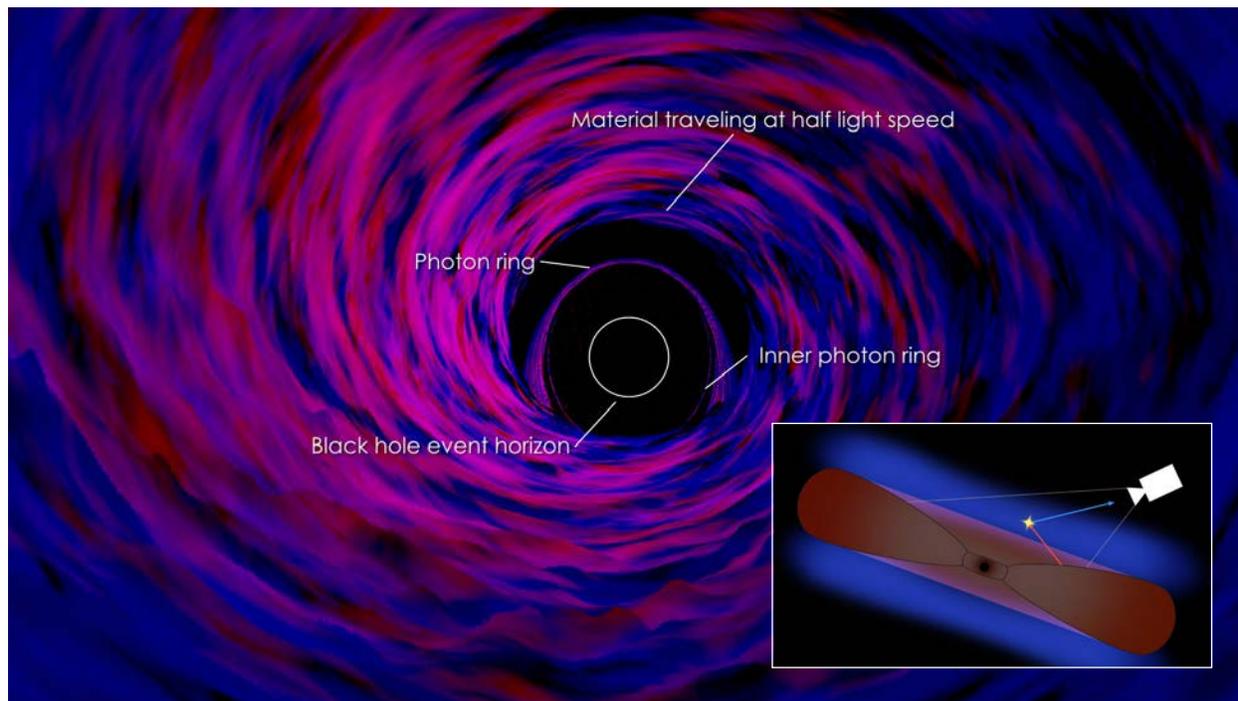
Dr. Jeremy Schnittman has helped to develop a process for modeling the inner region of a black hole's accretion disk, tracking the emission and propagation of X-rays through the highly curved space-time. This new study confirms long-held suspicions about how stellar-mass black holes produce their highest-energy photons and bridges the gap between theory and observation, showing from first principles that both hard and soft X-rays inevitably arise from gas spiraling toward a black hole.

Gas falling toward a black hole initially orbits around it and then accumulates into a flattened disk. The gas stored in this disk gradually spirals inward and becomes greatly compressed and heated as it nears the center. Ultimately reaching temperatures up to 12 million C—some 2,000 times hotter than the sun's surface—the gas shines brightly in low-energy, or soft, X-rays. For more than 40 years, however, observations have shown that black holes

also produce considerable amounts of hard X-rays, photons with energy tens to hundreds of times greater than soft X-rays. This higher-energy emission implies the presence of correspondingly hotter gas, with temperatures reaching billions of degrees.

Working with Julian Krolik (Johns Hopkins University) and Scott Noble (Rochester Institute of Technology), Schnittman developed a process for modeling the radiation transport of X-rays through the hot gas surrounding the black hole and comparing these results to observations. Noble developed a computer simulation solving all of the equations governing the complex motion of inflowing gas and its associated magnetic fields near an accreting black hole, while also taking into account Einstein's theory of relativity. The rising temperature, density and speed of the infalling gas dramatically amplify magnetic fields threading through the disk, which then exert additional influence on the gas. The result is a turbulent froth orbiting the black hole at speeds approaching the speed of light.

Over the years, improved X-ray observations provided mounting evidence that hard X-rays originated in a hot, tenuous corona above the disk, a struc-



*This animation of supercomputer data shows both low-energy X-rays (red) from the inner accretion disk and high-energy X-rays (blue) from the inner corona of a stellar-mass black hole. Particles in the corona scatter soft X-rays from the disk, resulting in hard X-ray emission. We view this scene from a perspective 45 degrees above the plane of the accretion disk. Inset: A sketch of showing the approximate relationships between the black hole, its accretion disk, the corona region and the viewing angle in the simulation. Credit: NASA's Goddard Space Flight Center/J. Schnittman, J. Krolik (JHU) and S. Noble (RIT)*

ture analogous to the hot corona that surrounds the sun. Noble's simulations showed that the strong magnetic fields in the disk naturally bubbled up out of the dense gas to form a corona.

Using the data generated by Noble's simulation, Schnittman developed tools to track how X-rays were emitted, absorbed, and scattered throughout both the accretion disk and the corona region. Combined, they demonstrate for the first time a direct connection between magnetic turbulence in the disk, the formation of a billion-degree corona, and the production of hard X-rays around an actively "feeding" black hole. In the corona, electrons and other particles move at appreciable fractions of the speed of light. When a low-energy X-ray from the disk travels through this region, it may collide with one of the fast-moving particles. The impact greatly increases the X-ray's energy through a process known as inverse Compton scattering, explaining the origin of the hard X-rays seen in observations. The results were published in *The Astrophysical Journal*.

The initial study was based on a non-rotating black hole. Schnittman and his collaborators are currently extending the results to spinning black holes, where rotation pulls the inner edge of the disk

further inward and conditions become even more extreme. They also plan a detailed comparison of their results to the wealth of X-ray observations now archived by NASA and other institutions.

### **IceCube, Neutrinos, and Lorentz Invariance**

The observation of two PeV-scale neutrino events reported by IceCube, a neutrino observatory located at the Amundsen-Scott South Pole Station in Antarctica, allowed Dr. Floyd Stecker to place strong constraints on Lorentz invariance violation in the neutrino sector. He first showed that at least one of the PeV IceCube events was of extragalactic origin, allowing him to derive an upper limit for the difference between putative superluminal neutrino and electron velocities. He then derived a new constraint on the superluminal electron velocity, obtained from Fermi observations of a Crab Nebula flare. His inference that the  $\sim$ GeV gamma rays from synchrotron emission in the flare were produced by electrons of energy up to  $\sim$ 5.1 PeV was used to derive a new, strong constraint on superluminal electron velocities. Stecker then used both constraints to obtain an upper limit on superluminal neutrino



*IceCube, located at the Amundsen-Scott South Pole Station in Antarctica, is the world's largest neutrino detector. The facility instruments a volume of roughly one cubic kilometer of clear Antarctic ice with 5,160 sensors at depths between 1,450 and 2,450 meters. The laboratory building shown here hosts the computers that collect the raw data. Credit: Felipe Pedreros. IceCube/NSF*

velocities alone that was many orders of magnitude better than the time-of-flight constraint obtained from the neutrino burst detected from SN 1987A. The study was submitted to Astroparticle Physics.

### **The Steep Decline of GRB Afterglows**

Dr. Demos Kazanas, working with J. Sultana (U. of Malta) and A. Mastichiadis (U. of Athens, Greece), addressed the puzzle of Swift X-ray afterglow light curves. The work is based on a model for the dissipation of GRB kinetic energy proposed a decade ago by Zazanas, Mastichiadis, and M. Georganopoulos (UMBC), which asserted a similarity between the conversion of energy stored in relativistic protons in a GRB blast wave and the explosion of a supercritical nuclear pile. The novel—and important—aspect of this study is the consideration of the effects of radiation emission on the kinematics of the GRB relativistic blast wave. The significance lies in that it connects the process of GRB radiation emission to the dynamics of the relativistic blast waves, and that it makes specific predictions about the prompt and afterglow GRB luminosity in agreement with observations. The results were published in *The Astrophysical Journal*.

## **PROJECTS IN OPERATION**

### **Fermi**

In operation since 2008, the Fermi Gamma-ray Space Telescope mission enjoys support from theorists in Code 663. In August, the mission celebrated the end of its five-year primary mission and entered an extended missions stage. The Fermi Project report is located in the **Astroparticle Physics Laboratory (661) section**.

## **PROJECTS IN DEVELOPMENT**

### **LISA Pathfinder**

A technology demonstration mission managed by ESA, LISA Pathfinder is due to launch in July 2015. Code 663 members are involved in the science team working group, and are participating in science mission operations planning and simulations to serve as part of the science operations team during in late 2015.

### **Neutron star Interior Composition Explorer Mission (NICER)**

NICER is currently in Phase C/D for installation on the International Space Station. Code 663 staff will provide theoretical and data analysis support for the mission. The NICER mission summary is reported in the **X-ray Astrophysics Laboratory (662) section**.

## **MISSION AND INSTRUMENT CONCEPTS**

### **ISS-Lobster**

**ISS-Lobster** is a wide-field X-ray transient all-sky monitor, proposed to be deployed on the ISS. The unique Lobster optics focus 0.3–5 keV X-rays and provide simultaneous wide field of view (900 square degrees), good sensitivity ( $10^{-11}$  erg/cm<sup>2</sup>sec in 2,000 sec), and good position resolution (1 arcmin). These characteristics predict a detection rate of numerous transient X-ray sources, including several per year of tidal disruption events, high redshift ( $z > 5$ ) GRBs, and, most importantly, X-ray counterparts of gravitational wave events observed by the LIGO network. ISS-Lobster was submitted as a Mission of Opportunity proposal in December 2012. The proposal received very strong reviews but the opportunity was cancelled due to lack of funding. The ISS-Lobster proposal will be re-submitted in December 2014.

### **Evolved LISA (eLISA)**

For more than a decade, the Laser Interferometer Space Antenna (LISA) has been the preferred mission concept for carrying out gravitational wave observations from space. Funding and programmatic constraints have forced NASA and the European Space Agency (ESA) to identify new mission concepts compatible with their respective programs. In Europe, this class of missions is called evolved LISA (eLISA), supported by the eLISA Consortium (<https://www.elisascience.org>). A small core group is supporting the European eLISA consortium and preparing for the Decadal 2020 activity in the U.S. with the goal of launching a space-based gravitational wave observatory.

In November 2013, the European Space Agency (ESA) chose the “Gravitational Universe” as the science theme for the L3 Cosmic Visions launch opportunity. A call for mission concepts to support this science theme will be issued later in the decade, with a nominal launch date of 2034. To support this selection, NASA completed in 2013 a technology development roadmap to bring several candidate technologies to TRL 5 level by 2018. The candidate technologies are micro-newton thrusters, a laser system, a phase meter and a telescope. In recent years the Strategic Astrophysics Technology (SAT) program has supported development of all four critical technologies. The Small Business Innovative Research (SBIR) program has also supported laser development. J. Livas leads the telescope work, and J. Camp leads the laser development at Goddard. W. Klipstein leads the phase meter development and J. Ziemer leads the microthruster effort at JPL.

The immediate milestone for the community is the successful conclusion of the LISA Pathfinder Mission (LPF) to be launched in 2015. LPF is a mission to demonstrate LISA technologies and to validate a noise model for inertial reference masses. It consists of an ESA payload called the LISA Test Package (LTP) and a NASA payload called the ST7 Disturbance Reduction System. J. I. Thorpe, NASA’s representative on the LPF Science Team, was joined by postdoc J. Slutsky to support mission science operational simulations and data analysis for the LPF mission as well as exploring possible extended mission phase experiments.

## TECHNOLOGY DEVELOPMENT FOR GRAVITATIONAL WAVE MISSIONS

The technologists of the Gravitational Wave Astrophysics Branch continued to study key and enabling technologies for space-based gravitational wave detection in 2013. In addition to developing technologies for a future U.S.-led gravitational wave mission, branch technologists are studying potential contributions to ESA’s eLISA mission concept. These efforts were led by branch scientists Camp, Livas, Numata, Stebbins, and Thorpe with help from both contract and civil-servant engineers. The technology-development efforts also provided educational opportunities for several students, including high school student Robert Buttles and graduate student Ryan Stein (Towson Univ.). Results from 2013’s technology development work were presented at several conferences, including the 13th International Conference on Topics in Astroparticle

and Underground Physics, the 221st American Astronomical Society Meeting, the 13th Meeting of the High Energy Astrophysics Division (HEAD), and the 2013 APS April Meeting.

The immediate milestone for the program is the successful completion of the LISA Pathfinder Mission (LPF), expected to launch in 2015. Thorpe, the U.S. LPF science team representative, along with Slutsky, are supporting science mission operations simulations for the validation of the gravitational inertial sensor noise model and developing a proposal for an extended mission.

Numata and Camp are pursuing the development of a planar-waveguide external cavity diode laser (PW-ECL) as a possible alternative to traditional NPROs and fiber lasers through the SBIR program with Redfern Integrated Optics in California. The first 1064 nm sample was delivered to Goddard in early 2013. Test results showed promising noise performance and a second laser with higher output power is scheduled for delivery in late 2013 and will be tested together with the Yb pre- and power-amplifier as an all-waveguide-based laser system.

Livas, together with postdoctoral fellow Shannon Sankar (U. Florida) and collaborators Peter Blake, Joe Howard, Len Seals, Petar Arsenovic, and Ron Shiri—all in Code 551, the Optics Branch of Goddard’s Instrument Systems & Technology Division—completed a study with an industrial partner to do a focused design and engineering study for a telescope for a space-based mission that includes an explicit consideration of design-for-manufacturing requirements, an expertise that the Goddard team does not have. Procurement of a prototype telescope is in progress to support an experimental test program to verify the performance of the design. As part of the design study, Sankar, Shiri and Seals are investigating the feasibility of using amplitude masks for scattered light suppression. The masks would be implemented with carbon nanotube technology developed by John Hagopian (551). Shiri has an IRAD award for this work.

## AWARDS

Dr. Alice Harding’s research on pulsars won the 2013 Bruno Rossi Prize from the American Astronomical Society, awarded jointly with Dr. Roger Romani from Stanford University, “for establishing a theoretical framework for understanding gamma-ray pulsars” and the Robert H. Goddard Award of Merit “for a career of excellence in the theoretical understanding pulsars.”

The Goddard Honor Award for Diversity and Equal Employment Opportunity went to Dr. John Baker “for attracting a large and diverse group of highly qualified postdocs to Goddard with significant representation of under-represented classes.”

In December, U.S. Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs Kerri-Ann Jones honored Dr. Vigdor Teplitz (663 emeritus) with an individual certificate of appreciation for “exceptional, sustained performance in furthering the international cooperation goals outlined in the President’s June 2010 National Space Policy.” The award recognized efforts to assist NASA in getting South Africa to join the president’s Asteroid Initiative and, in particular, to obtain access to a specific South African radar.

## NEW FACES

### Tehani Finch



Tehani joined the gravitational astrophysics lab at ASD as an NPP fellow in September 2013. He arrives after four years as a Lecturer at Howard University, where he also obtained his doctorate in theoretical physics under Dr. Tristan Hubsch. His research interests include construction

of new coordinate systems for black hole geometries, higher-dimensional relativity, causal structure of time-dependent space-times, and the gravitational wave forms produced by merging binary black holes. He currently works under the supervision of John Baker on applying the recently developed ten-dex-vortex formalism for space-time curvature visualization to mergers of black holes with spin. He also looks forward to investigating the knowledge that can be gleaned about constraints on dark matter annihilation involving the Penrose process between the static limit and the horizon of a rotating black hole, through the use of novel coordinates. Tehani is quite pleased to be able to learn from and interact with the astrophysics community at Goddard and eagerly anticipates the chance to broaden the scope of his research.

# Observational Cosmology Laboratory



Dr. Jonathan Gardner  
*Lab Chief*



Dr. Stephen Rinehart  
*Associate Lab Chief*

## Laboratory Overview

The Observational Cosmology Laboratory (Code 665) investigates the origin, evolution, contents and ultimate fate of the universe. Scientists seek to understand what powered the Big Bang; the size, shape, and matter-energy content of the universe; when the first stars and galaxies appeared and their evolution over cosmic time; and the nature of the mysterious dark energy that is driving the universe apart. We analyze data from past and current missions to puzzle out the nature of galaxies and the history of the universe and we develop new techniques, new technologies, new cameras and state-of-the-art detectors. Experimental test beds and air- or balloon-borne instruments pave the way for new space missions. Laboratory astrophysics experiments provide new comparisons for interpreting infrared data from missions such as the Spitzer, Herschel, and James Webb Space Telescopes. In addition to the civil servant staff, the laboratory has 62 contract and university scientists, engineers, technicians, post docs, and grad students.

## Staff List

Scientist	Research Interest	Project/Mission	Affiliations
Dominic Benford	Astronomical Instrumentation; Galaxy formation and evolution	WFIRST-AFTA HAWC++ BETTII PIPER WISE	Program Scientist (HQ) Institutional Principal Investigator Co-Investigator Co-Investigator Deputy Project Scientist
David Chuss	Cosmic microwave background; CMB polarimetry	LAMBDA CLASS PIPER HAWC+	Director Institutional Lead Co-Investigator Co-Investigator
Eli Dwek	Formation and evolution of dust; extragalactic background light; galaxy evolution		
Jonathan Gardner	Galaxy formation and evolution	JWST Euclid	Deputy Senior Project Scientist Consortium Member
Matthew Greenhouse	Active galaxies; infrared astronomy	JWST	ISIM Project Scientist

<b>Scientist</b>	<b>Research Interest</b>	<b>Project/Mission</b>	<b>Affiliations</b>
Alan Kogut	Cosmic microwave background; far-IR instrumentation; diffuse radio continuum	PIPER PIXIE NASA Scientific Balloon Program	Principal Investigator Principal Investigator Deputy Project Scientist
Jeffrey Kruk	Dark energy; stellar evolution; instrumentation	WFIRST-AFTA HST ACCESS	Study Instrument Scientist Observatory Project Scientist Institutional Lead
John Mather	Cosmology; instrumentation	JWST	Senior Project Scientist
Harvey Moseley	Cosmology; infrared astronomy instrumentation	JWST Microshutter Array PIPER CLASS HAWC++ FORTIS	Principal Investigator Co-Investigator Co-Investigator Co-Investigator Co-Investigator
Susan Neff	Galaxy formation and evolution, activity cycles	Cosmic Origins Program GALEX	Chief Scientist Project Scientist
Deborah Padgett	Debris disks, star formation	Cosmic Origins Program WISE WFIRST-AFTA	Deputy Chief Scientist Co-Investigator Study Scientist
Bernard Rauscher	Infrared astronomy instrumentation, galaxy formation, cosmology	JWST ACCESS WFIRST-AFTA	Deputy ISIM Project Scientist Co-Investigator Study Scientist
Jane Rigby	Star-forming galaxies, active galactic nuclei	JWST	Deputy Project Scientist for Operations
Stephen Rinehart	Astronomical instrumentation, interferometry, star and planet formation	TESS BETTII	Project Scientist Principal Investigator
Robert Silverberg	IR astronomy instrumentation	BETTII	Emeritus
George Sonneborn	Supernovae, massive stars	JWST	Project Scientist for Operations
Amber Straughn	Galaxy formation and evolution	JWST WFIRST-AFTA	Deputy Project Scientist for Communications Study Scientist
Eric Switzer	Cosmic microwave background, large-scale structure	PIPER WFIRST-AFTA	Co-Investigator Study Scientist
Edward Wollack	Astronomical instrumentation, cosmology	NASA Engineering Safety Center ACTpol CLASS HAWC++ GISMO PIPER WFIRST-AFTA	Deputy Chief Scientist Co-Investigator Co-Investigator Co-Investigator Co-Investigator Co-Investigator Study Scientist



*This composite of the giant barred spiral galaxy NGC 6872 combines far-ultraviolet (1528 Å) data from NASA's GALEX with optical images from the European Southern Observatory's Very Large Telescope and 3.6-micron infrared data acquired by NASA's Spitzer Space Telescope. A previously unsuspected tidal dwarf galaxy candidate (circled) appears only in the ultraviolet, indicating the presence of many hot young stars. IC 4970, the small disk galaxy interacting with NGC 6872, is located above the spiral's central region. The spiral is over 160 kpc across from the tip of one outstretched arm to the tip of the other, which makes it about five times the size of the Milky Way. Images of lower resolution from the Digital Sky Survey were used to fill in marginal areas not covered by the other data. Credit: NASA's Goddard Space Flight Center/ESO/JPL-Caltech/DSS*

## SCIENCE HIGHLIGHT

### The Condor Spreads its Wings

The barred spiral galaxy NGC 6872, the Condor galaxy, is the largest-known spiral galaxy, as reported by Rafael Eufrazio, Eli Dwek, Richard Arendt, and Duilia de Mello at the AAS winter meeting in January 2013. For decades, the Condor was counted among the largest-known galaxies, but the capabilities of GALEX to detect ultraviolet light from young stars enabled determination of its true extent.

The galaxy is much larger in the ultraviolet than in any other wavelength regime due to star formation triggered by an interaction with its closest companion to the north, the lenticular galaxy IC 4970. This discovery was part of a multiyear effort to study star formation in nearby spiral galaxies from the UV to radio. The galaxy's extended UV and HI disk is longer than 160 kpc in diameter. The disk is inclined 45° towards our line-of-sight and, despite interaction with its companion, the Condor's rotation curve is quite regular and undisturbed.

The outer parts of the disk are almost entirely blue, suggesting the presence of young stellar populations full of massive hot stars. The companion possesses only 10 to 20 percent of the Condor galaxy's mass, which is greater than  $2 \times 10^{11} M_{\text{sun}}$  in stars, with an average rate of star formation around  $5 M_{\text{sun}}$  per year. The interaction disturbed the morphology of the galaxy, but did not significantly affect its stellar or gas masses. Over the entire duration of the interaction, the total stellar mass formed does not account for even 1 percent of the Condor's current stellar mass. A detailed study of the Condor bar also shows that this structure was in place for the last few gigayears and was minimally affected by the collision.

Another interesting product of this interaction is shown in the upper-right corner of the image, on the edge of the Condor's spiral arm. It resembles a tidal dwarf galaxy in the process of formation. The study also included Fernanda Urrutia-Viscarra and Claudia Mendes de Oliveira at the University of São Paulo in Brazil and Dimitri Gadotti at the European Southern Observatory in Santiago, Chile.



*Marking a huge mission milestone for the James Webb Space Telescope, the last three of the 18 flight primary mirror segments arrived at NASA's Goddard on Dec. 16, 2013. After traveling across the country, the mirrors were prepped to enter a Goddard clean room for inspections. Credit: NASA Goddard/Chris Gunn*

## PROJECTS IN OPERATION

### Hubble Space Telescope

The Hubble Space Telescope (HST) is discussed in the [Code 667 laboratory section](#) and includes participation by Code 665 member Jeffrey Kruk as the Observatory Project Scientist.

## PROJECTS IN DEVELOPMENT

### James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large (6.5m), cold (50K), facility-class general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point. It is the successor to the Hubble and Spitzer space telescopes. Its science goals include detecting the first galaxies to form in the early universe, galaxy evolution, star formation,

exoplanets and objects in our solar system. Time on the telescope will be allocated to the community through annual peer-reviewed proposals in a manner similar to Hubble. The prime contractor is Northrop Grumman; the Science and Operations Center is located at the Space Telescope Science Institute. JWST is a partnership between NASA and the European and Canadian space agencies.

The ASD provides scientific direction for JWST through a team consisting of 11 project scientists. The Senior Project Scientist is John Mather, his deputy is Jonathan Gardner and his technical deputy is Malcolm Niedner. The other members of the team: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles Bowers (deputy); Randy Kimble (Integration and Test); George Sonneborn (Operations), Jane Rigby (deputy) and Amber Straughn (Communications). In addition, Stefanie Milam is currently on detail from the Planetary Sciences Division to study solar system observations



*Goddard engineer Ed Shade puts the final touches on thermal blankets in a Space Environment Simulator, a vacuum chamber used to test JWST components. The blankets, made of aluminized kapton, cover wiring on the floor to prevent the heat they create from contaminating the other parts of the test bed. Credit: NASA/Chris Gunn*

with JWST. ASD science staff members are also directly involved in the provision of key flight systems for the JWST near-infrared multi-object spectrometer (NIRSpec), including its detector and microshutter array systems.

Mather chairs the JWST Science Working Group (SWG), and the Project Scientists work closely with the management and engineering teams, participating in reviews, project meetings, serving on change-configuration boards, and participating in decisions. In 2006, the JWST SWG published a thorough description of the JWST science goals and technical implementation as a special issue of the refereed journal *Space Science Reviews*. It has since also updated and extended the science case in a series of white papers that include astrobology, dark energy, exoplanet coronagraphy, exoplanet transits, first-light galaxies, resolved stellar population, and solar system observations. The *Space Science Reviews* paper and the white papers are available from [jwst.gsfc.nasa.gov/scientists.html](http://jwst.gsfc.nasa.gov/scientists.html). There were two conferences for community discussion of JWST science in 2007 and 2011. The next conference is likely to be in 2015.

The JWST Project is currently in development, and is conducting the Integration and Test (I&T)

phase for many systems. The budget and schedule went through a replan in 2011 and the mission is now fully funded for launch in 2018; there has been no change to the budget or schedule since the replan. The Integrated Science Instrument Module (ISIM) consists of the four science instruments and nine subsystems. ISIM began its integration and testing phase in 2011. In 2013, two instruments, the Mid-Infrared Instrument and the Fine Guidance Sensor/Near-Infrared Imager and Slitless Spectrograph were integrated into the ISIM structure, which went through its first cryovacuum test. The other two instruments, the Near-Infrared Camera and the Near-Infrared Spectrograph, were delivered to Goddard. The ISIM and its four instruments will undergo its second cryovacuum test in 2014, with a third planned for 2015.

The ASD is directly responsible for provision of two flight systems, both within the Near-Infrared Spectrograph (NIRSpec), an instrument that is part of the ESA contribution to the mission. The Microshutter Assembly (MSA) is led by PI Harvey Moseley with contributions from a number of contractor scientists. The MSA will enable simultaneous spectra of more than 100 objects—the first time that a true multi-object spectrograph has



*ASD outreach: NASA 2013 Real World/In World Engineering Design Challenge winners visit Goddard and meet with Nobel Laureate Dr. John Mather. Credit: Darryl Mitchell*

flown in space. An initial MSA system was delivered to ESA in 2010; a replacement is currently being made. The NIRSpec detector system is also being built at Goddard, under the leadership of PI Bernard Rauscher. Moseley and Rauscher are members of the NIRSpec Science Team and will participate in their Guaranteed Time Observations.

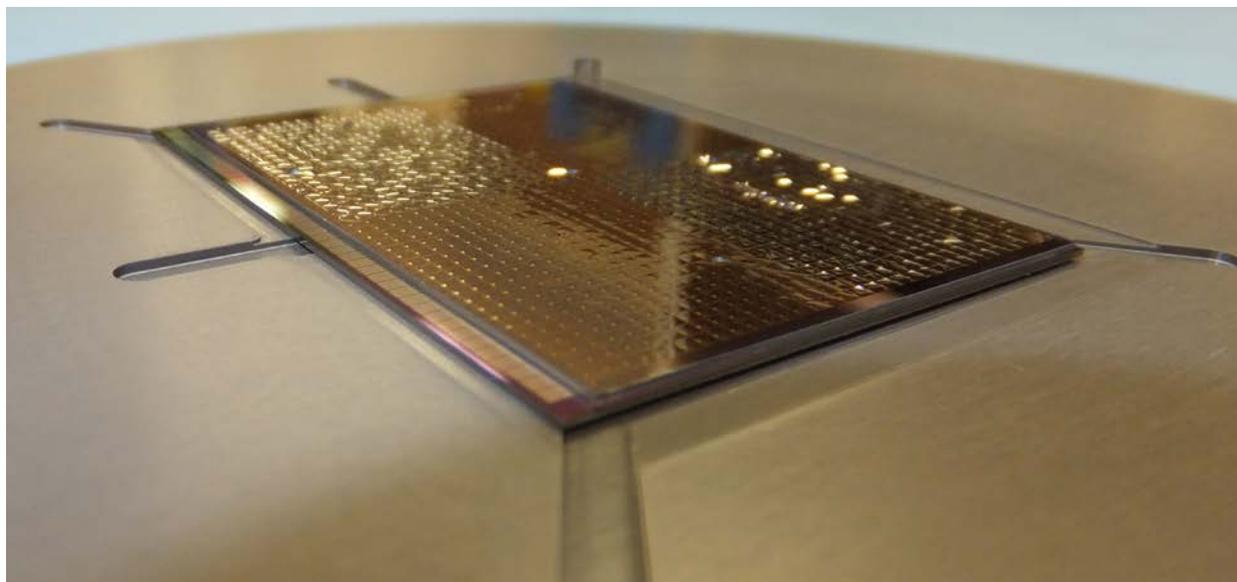
All of the flight primary mirror segments and secondary and tertiary mirrors have been completed and were delivered to Goddard in 2013. The center section of the flight backplane underwent cryovacuum testing in 2013, and the two deployed side wings of the backplane were also completed in 2013. The primary mirror will be assembled onto the back plane in the Goddard clean room over the next few years.

When the primary mirror is complete and the ISIM is finished with its I&T, the two will be put together and tested in the Johnson Space Center Chamber A. The JWST project has modified the historic Chamber A for use in JWST testing by installing a gaseous helium shroud. During 2013, a clean room was constructed outside the chamber.

Development of the JWST Science and Operations Center at Space Telescope Science Institute is

progressing with the rest of the project. Analysis of the Science Operations Design Reference Mission allowed a first look at scheduling and efficiency. Additional science tools include an exposure time calculator, a point spread function simulator and the JWST astronomer's proposal tool. A System Design Review was completed for the Data Management System, which will process, calibrate and archive the science and engineering data.

Outreach to the scientific community in 2013 included Town Halls at the American Astronomical Society winter meeting and at the Division of Planetary Science meeting. Public outreach and communications highlights for 2013 included a tremendously successful presence at the South by Southwest Festival in Austin, Texas. With activities centered on the JWST full-scale model, JWST personnel interacted directly with more than 15,000 people and reached more than 4 million through social media. The JWST social media team now has nearly 160,000 Facebook friends, 100,000 Twitter followers and 400,000 total video views. The JWST website underwent a major update and there were several press releases or web features each month.



*The 1,280-pixel pathfinder array, which is hybridized to an SQUID Multiplexer from NIST Boulder.*

### **HAWC+ for SOFIA**

The HAWC+ detector effort for NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) is led by Johannes Staguhn of ASD's Observational Cosmology Laboratory and Johns Hopkins University. The core development team includes Dominic Benford, Steve Maher (also SSAI), Moseley, Elmer Sharp (also GST) and Ed Wollack, along with Christine Jhabvala and Tim Miller from Goddard's Detector Systems Branch. The HAWC+ project PI is Darren Dowell of the Jet Propulsion Laboratory. A prototype pathfinder kilopixels detector array with integrated cold readout was built and tested this year. This has been a major step toward the delivery of four flight arrays for the instrument, scheduled for the first half of 2015.

HAWC+ will give SOFIA the ability to study magnetic fields in the molecular material from which stars emerge and the ability to efficiently obtain large maps of the emission from dust. The scientific rationale for HAWC+ polarimetry arises from the fact that the far-infrared ( $\lambda = 30\text{--}300\ \mu\text{m}$ ) continuum dust emission from Galactic sources has been found to show linear polarization of 5 percent or greater, and that this polarization can be used to study the magnetic field in the emission regions.

Magnetic fields are known to exist throughout the universe and may be a crucial ingredient in the formation of stars and molecular clouds. Only a few types of magnetic field measurement are possible. Among them, far-infrared polarimetry is particularly well suited to the study of magnetic fields in the

molecular material where stars are born. In addition to observing the orientation of galactic magnetic fields in dense gas in our own galaxy, HAWC+ will measure the global orientation of magnetic fields in other galaxies. These observations can address outstanding problems in galactic dynamo theory, help discriminate between theories and models for galactic winds, and help understand the FIR-radio correlation in galaxies. The phenomenon of interstellar polarization was discovered by Hall and Hiltner in 1949, but the mechanism by which grains align with magnetic fields is still one of the longest-standing mysteries of ISM physics. The 2010 Decadal Survey stressed the importance of polarimetry in understanding magnetic fields: "Using aligned dust as a tracer for magnetic fields requires understanding the shapes and optical properties of dust grains and how variations in the degree of dust alignment depend on local conditions in clouds." Through its combination of spectral coverage, sensitivity, high angular resolution, and wide field in the far infrared, HAWC+ can provide crucial tests of theories of grain alignment.

### **WMAP FINAL RESULTS**

The Wilkinson Microwave Anisotropy Probe (WMAP) has mapped the cosmic microwave background (CMB) radiation—the oldest light in the universe—and helped establish a simple and comprehensive cosmological model connecting the physics of the very early universe to the properties observed

today. In this standard model, the universe is flat, homogeneous, and isotropic on large scales. The WMAP team includes ASD scientists Bennett (PI, now at JHU), Hinshaw (now at UBC), Kogut, and Wollack.

The WMAP mission was selected by NASA in 1996 as the result of an open competition, confirmed for development in 1997, and was built and ready for launch only four years later, on-schedule and on-budget. Launched as MAP on June 30, 2001, the spacecraft was later renamed WMAP to honor David T. Wilkinson, a Princeton University cosmologist and a founding science team member who died in September 2002. Once at its observing station near the second Lagrange point of the Earth-Sun system, a million miles from Earth in the direction opposite the sun, WMAP scanned the heavens and precisely recorded tiny temperature fluctuations across the sky. Its first results were published in February 2003, with major updates in 2005, 2007, 2009, 2011, and a final data release in 2013. Having completed its mission to “take measure of our universe,” its data stream has ceased and the spacecraft now resides in a parking orbit about the sun. The science team gratefully salutes the innovation of the technicians, engineers, and countless contributors to WMAP’s voyage and its ultimate scientific success.

## MISSION AND INSTRUMENT CONCEPTS

### Primordial Inflation Explorer (PIXIE)

The advent of a standard model for cosmology is based in part on the concept of inflation, a rapid period of superluminal expansion in the early universe. The exponential growth of the scale size during inflation neatly explains the observed conditions of our universe, but relies on extrapolation of physics to energies a trillion times beyond those accessible to direct experimentation in particle accelerators. The Primordial Inflation Explorer (PIXIE) will test the inflationary paradigm by searching for the “smoking gun” signature of primordial inflation in the linear polarization of the cosmic microwave background (CMB).

PIXIE is an Explorer mission concept to detect and characterize the signature of primordial inflation. Principal Investigator Alan Kogut leads a team including Goddard Co-Investigators Dave Chuss, Eli Dwek, Dale Fixsen, Harvey Moseley and Ed Wollack. PIXIE’s innovative design uses a



*Artist's concept of the PIXIE observatory in low Earth orbit.*

multi-moded “light bucket” and a polarizing Fourier Transform Spectrometer to measure both the linear polarization and spectral energy distribution of the CMB and diffuse astrophysical foregrounds. PIXIE will measure the frequency spectra in 400 spectral bands from 30 GHz to 6 THz for each of the Stokes I, Q, and U parameters in each of 49,152 independent pixels covering the full sky. The optical design achieves sensitivity comparable to focal-plane arrays of 10,000 detectors while requiring only 4 detectors.

The combination of sensitivity and broad spectral coverage answers exciting questions across cosmic history. PIXIE’s primary science goal is the characterization of primordial gravity waves through their signature in CMB polarization. PIXIE will measure linear polarization to a sensitivity of 70 nK per  $1^\circ \times 1^\circ$  pixel. Averaged over the sky, PIXIE can detect CMB polarization to 3 nK sensitivity, a factor of 10 below the minimum signal predicted from large-field inflation models. In addition, PIXIE measurements of the frequency spectrum test astrophysical processes ranging from the nature of the first stars at reionization, to the star formation history of the universe, and to physical conditions within the interstellar medium of the Galaxy.

### Wide Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA)

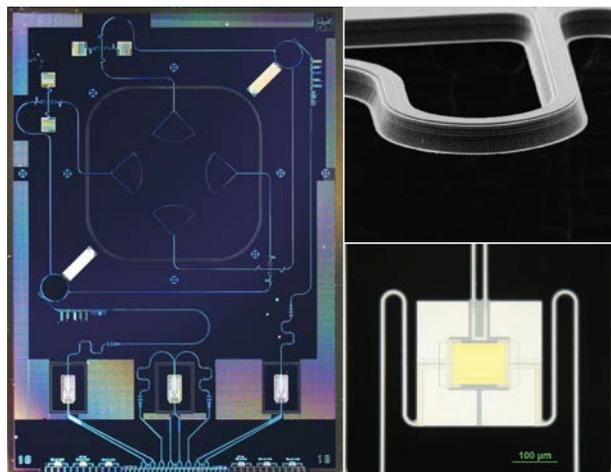
WFIRST-AFTA is a concept currently being studied as an astrophysics mission for the 2020s. Code 665 members Kruk, Straughn, Rauscher, and Wollack provide support for the mission study, on which we report in the [Exoplanet Laboratory \(667\) section](#).

## TECHNOLOGY DEVELOPMENT / SUBORBITAL / BALLOON

### Detecting CMB Polarization

Recent advances in cosmology hint that the universe underwent a brief period of rapid expansion called inflation early in its history. If inflation occurred, the gravitational waves it produced would have polarized the cosmic microwave background (CMB) in a particular pattern. To measure this faint signature requires the development of instruments with high sensitivity, precision control over systematic effects, and multiple frequencies for removal of polarized galactic foregrounds.

Wollack, Chuss, Moseley, and Karwan Rostem in ASD's Observational Cosmology Laboratory, along with team members Kevin Denis, Thomas Stevenson, and Kongpop U-Yen in Goddard's Applied Engineering and Technology Directorate, are developing detectors for measurement of the polarization of the CMB. These micromachined silicon sensors are waveguide-coupled and employ Transition-Edge Sensing (TES) bolometers realized on a mono-crystalline silicon substrate. In the sensor concept, radiation from the feedhorn is coupled onto superconducting microstrip circuitry using a planar ortho-mode transducer and subsequent-



Left: A CLASS 40-GHz-detector microwave circuit. Opposite probe antennas (center) couple to a common polarization on the sky once a waveguide and feedhorn are connected. The signal in each polarization is filtered to define the band before thermally coupling to a TES. Right: At top, a scanning electron micrograph image of one of the silicon legs that supports the TES membrane. Below, the rectangle at image center is the TES thermally-isolated membrane.

ly filtered and detected on chip. This and related technologies for characterization of CMB polarization will be demonstrated in the Cosmology Large Angular Scale Surveyor (CLASS) instrument, a project led by Johns Hopkins University to be deployed in Chile's Atacama Desert.

### The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII)

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an 8-meter boom interferometer to operate in the far-infrared (30-90  $\mu\text{m}$ ) on a high-altitude balloon. The long baseline will provide unprecedented angular resolution ( $\sim 0.5''$ ) in this band, and the high atmospheric transmission at balloon altitudes will allow the unique double-Fourier instrument on BETTII to obtain spectral resolution up to  $R \equiv \lambda/\Delta\lambda \sim 200$ . The combination of these capabilities will provide spatially resolved spectroscopy on astrophysically important sources, exploring the physical processes that lurk below the resolution limits of current FIR facilities. The first flight of BETTII, planned for fall 2015, will focus on star-forming clusters, providing powerful new constraints on models of cluster formation.

The BETTII project is now three years old, and is proceeding on schedule. All major elements of the design are complete, and all long-lead procurements are in process. The metering truss for the external optics was completed in August 2012; the exoskeleton for electronics and control system components was constructed in summer of 2013 (although layout modifications continue to be made); and the instrument cryostat is on order, with delivery of all components expected in early 2014. The exoskeleton is currently being used for testing of the gondola control system, including both sensors and control mechanisms, and all individual mechanisms have been carefully tested under flight-like conditions. Going forward, we are completing the final designs: a few elements, such as the optical layout of the near-infrared angle sensor, are being redesigned to take advantage of lessons learned in the course of the project. But the majority of the effort in the coming year will be focused on testing and integration of components into the system. By the end of 2014, we anticipate having the complete payload in the high bay, with full system testing occurring in early 2015.

Data acquired with BETTII will be complementary to observations with space observato-

ries such as Herschel and the James Webb Space Telescope, exploring the FIR wavelength range with unprecedented high angular resolution. These data will be powerful tools for understanding star formation in clusters, and with future flights, for understanding active galactic nuclei and the late stages of stellar evolution. In addition, the successful flight of BETTII will pave the way for future space interferometry, by validating key technologies and techniques (such as wide-field interferometry). As discussed in the new Astrophysics Roadmap, “Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades,” interferometry will play a key role in the future of astrophysics, and BETTII is the first step toward realizing these ambitions.

The BETTII project is a collaboration between Goddard, the University of Maryland, and Cardiff University, with assistance from the Far-Infrared Telescope Experiment team in Japan. The BETTII team includes ASD scientists Rinehart, Barry, Benford, Fixsen, Bill Danchi, Johannes Staguhn, Robert Silverberg (Emeritus), as well as David Leisawitz (Science Proposal Support Office), Christine Jhabvala (Instrument Systems & Technology Division) and Lee Mundy (UMCP). The project also has had contributions from a UMCP graduate student (Maxime Rizzo) and a number of undergraduates from multiple institutions. Information on BETTII interns can be found on the BETTII website (<http://asd.gsfc.nasa.gov/bettii>)

## Primordial Inflation Polarization Explorer

The Primordial Inflation Polarization Explorer (PIPER) is a balloon-borne mission to measure the polarization of the cosmic microwave background (CMB) in search of the signature of primordial gravity waves excited by an inflationary epoch in the early universe. Kogut is the PI, and ASD team members include Benford, Chuss, Fixsen, Lazear, Lowe, Mirel, Moseley, Sharp, Staguhn, Switzer, Weston, and Wollack.

PIPER addresses fundamental questions at the intersection of physics and cosmology. Cosmology posits a period called inflation, shortly after the Big Bang, when the expansion of space-time accelerated dramatically to “inflate” the universe from subatomic to macroscopic scales. Inflation neatly explains the initial conditions of Big Bang cosmology (a spatially flat, homogeneous universe with scale-in-



*The PIPER Variable-Delay Polarization Modulator. The polarizer uses 1.5 km of 36  $\mu\text{m}$  diameter wire, held to 3-micron precision across a 40-cm aperture. The VPM operates at 1.5 K using simple linear translation of the reflective mirror.*

variant density perturbations), but it relies on the extrapolation of physics to energies a trillion times above those accessible to direct experimentation in particle accelerators. PIPER will test inflation by measuring the polarization pattern in the CMB caused by a background of gravitational radiation created during an inflationary epoch. Such a signal is expected to exist, with observable amplitude and a unique spatial signature. Detection of the gravity-wave signature of inflation would have profound consequences for both cosmology and high-energy physics. It would establish inflation as a physical reality, determine the relevant energy scale, and probe physics at energies near Grand Unification to provide direct observational input for a “final theory” of quantum mechanics and gravity.

PIPER achieves unprecedented sensitivity by combining several technologies pioneered by Goddard researchers.

**Large-format bolometric detectors.** PIPER will fly 5,120 transition-edge superconducting bolometers in a Backshort-Under-Grid (BUG) archi-

texture. By moving all wiring beneath the array, the BUG architecture allows efficient 2-dimensional tilting of the focal plane without any reflective elements that would reduce the optical efficiency. PIPER has produced its first 32 x 40 bolometer arrays for characterization. Similar arrays will be used in the GISMO, GISMO-2, and HAWC+ detectors and are potential candidates to fly on a future large mission (the Inflation Probe).

A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized from unpolarized radiation. The fast (3 Hz) modulation allows full characterization of the incident radiation into Stokes I, Q, U, and V parameters on time scales fast compared to instrument drifts or beam motion on the sky. Unlike half-wave plates (which modulate between the Stokes linear polarization parameters Q and U), the VPM modulates between linear (Stokes Q) and circular (Stokes V) polarization. The sky at millimeter wavelengths is thought to have negligible circular polarization. By comparing the faint linear polarization to a null signal, the VPM mitigates most instrumental artifacts associated with the antenna beam patterns, enabling a significant reduction in the overall error budget. VPM development for PIPER complements technology development for the Inflation Probe.

**Fully cryogenic optics.** PIPER's twin telescopes fit within the old ARCADE dewar and will operate at 1.5 K to provide background-limited sensitivity. Maintaining all optical elements at 1.5 K or colder improves mapping speed by a factor of 10 compared to ambient optics, allowing PIPER to use conventional (overnight) balloon flights instead of more challenging Antarctic operations.

PIPER's use of conventional ballooning allows nighttime observations when the sun has set. This in turn allows the mission to rapidly scan large fractions of the sky. By combining flights from Northern and Southern Hemisphere launch sites, PIPER can achieve nearly full-sky coverage. PIPER is the only balloon mission capable of observing on angular scales larger than  $20^\circ$ , where the inflationary signal is expected to be largest.

PIPER will map the sky in both linear and circular polarization, at wavelengths of 1500, 1100, 850, and 500  $\mu\text{m}$  (frequencies 200, 270, 350, and 600 GHz). It will detect the signature of inflationary gravity waves to a factor of 3 fainter than the lowest value predicted by inflationary models. The unbiased survey of submillimeter polarization will

also provide an important probe of interstellar cirrus dust and the large-scale structure of the Galactic magnetic field and will be the first sky survey in circular polarization at these wavelengths.

## AWARDS

In 2013, numerous awards went to members of the Observational Cosmology Lab.

Dale Fixsen won the NASA Exceptional Public Achievement Medal, which recognizes substantial improvement in operations, efficiency, service, financial savings, science, or technology which contributes to the mission of NASA.

Harvey Moseley was honored with the SPIE George W. Goddard Award in recognition of his extraordinary inventions of superconducting imaging arrays for astronomy, ranging from submillimeter bolometers to energy sensitive X-ray microcalorimeters, and even dark matter detectors, as well as microshutter arrays for the James Webb Space Telescope near-infrared spectrometer. The award is given annually by SPIE, the international society of optics and photonics, in recognition of exceptional achievement in optical or photonic instrumentation for aerospace, atmospheric science, or astronomy.

Stephen Rinehart accepted the Robert H. Goddard Mentoring Team award on behalf of the BETTII team, which was recognized for "providing consistent and excellent mentorship to undergraduate students and hands-on engineering experience contributing to science." Amber Straughn won the Goddard Award for Outreach for "outstanding leadership in developing and operating the NASA JWST events at the South by Southwest Festival."

Jane Rigby's efforts "promoting the inclusion of lesbian, gay, bisexual and transgender people at NASA and within professional astronomy" were recognized with the Goddard Award for Diversity and Equal Employment Opportunity. She was previously recognized in 2012 for work using gravitational lensing to map a distant galaxy in unprecedented detail, winning a Goddard Award for Scientific Achievement. Also winning the award that year was Eli Dwek, who was recognized for his new, detailed, and observationally confirmed models of the formation, evolution, and destruction of cosmic dust grains, from supernovae to shock waves and star-forming regions.

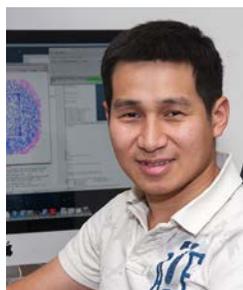
## NEW FACES

### Jennifer Scott



Jennifer joined ASD in September 2013 as a Senior NPP Fellow on a six-month appointment. She received her Ph.D. from the University of Arizona in 2002 and did post-doctoral work at the Space Telescope Science Institute and at Goddard as a National Research Council Fellow. She is now back at Goddard while on sabbatical leave from Towson University, where she is an Associate Professor in the Department of Physics, Astronomy, and Geosciences. Jennifer's research interests are the intergalactic medium and outflows from active galactic nuclei (AGN) and the environments of their host galaxies. She uses spectrograph data from the Hubble Space Telescope extensively in her work and is particularly focused on combining the spectra of AGN with ground-based imaging to characterize their environments and examine their relationship to the mechanism that fuels their supermassive black holes.

### Chun Ly



Chun received his M.Sc. and Ph.D. from the University of California, Los Angeles, for research that focused on studying galaxy evolution over the past 10 gigayears, under advisor Prof. Matthew Malkan. After graduating, he was a Giacconi Postdoctoral Fellow at the Space Telescope Science Institute. He joined ASD's Observational Cosmology Lab in October 2013 as an NPP Fellow. His primary research while at NASA is on the chemical enrichment and evolution of galaxies over cosmic time. In particular, he is conducting a new optical and near-infrared spectroscopic survey of low-mass star-forming galaxies to provide new constraints on baryonic processes—star formation and gas flows—that drive galaxy formation and evolution. Such observations are key to future missions, such as the James Webb Space Telescope, which aim to determine how galaxies formed, evolved, and enriched the cosmos. For his research, Chun utilizes six-

10-meter ground-based telescopes, which includes the MMT, Magellan, Subaru, and Keck. He plans to combine his ground-based work with high-resolution imaging from the Hubble Space Telescope to study the sites of star formation and the physical conditions of the interstellar medium in these “pristine” galaxies.

### Eric Switzer



Eric earned his Ph.D. in physics at Princeton University, where he studied cosmological recombination of helium and was part of the team that built the Atacama Cosmology Telescope. After graduating, he became a postdoc at the Kavli Institute for Cosmological Physics and then at the Canadian Institute for Theoretical Astrophysics. At CITA, he analyzed the statistical distribution of matter when the universe was half its present size, using the 21 cm transition of neutral hydrogen and data acquired with the Green Bank Telescope. This required the development of new methods to handle foregrounds that are 1,000 times larger than the cosmological signal. His research relates observations of diffuse cosmic background radiation to models of our universe at large. Eric arrived at Goddard in August 2013 as a new civil servant and has joined the PIPER collaboration. PIPER is a balloon-borne CMB polarimeter designed to measure the traces of gravitational waves in the early universe. He is excited to be part of the Goddard cosmology community and looks forward to future missions like PIXIE and WFIRST.

### Omid Noroozian



Omid earned his Ph.D. in 2012 at the California Institute of Technology, where he worked with Jonas Zmuidzinas, Chief Technologist at JPL, on developing superconducting microresonator detector arrays for submillimeter and far-infrared imaging with the Cerro Chajnantor Atacama Telescope. After graduation he moved to Boulder, Colorado, where he worked as a postdoc with Joel

Ullom and Kent Irwin at the Quantum Sensors Group at the National Institute of Standards and Technology. While there, he demonstrated for the first time high-resolution gamma-ray/X-ray spectroscopy using microwave SQUID multiplexing readout of transition-edge sensor arrays. Omid joined ASD as an NPP Fellow in July 2013 to work with Harvey Moseley in the Observational Cosmology Laboratory. He is currently working as part of a team to develop an ultra-miniature on-chip spectrometer for submillimeter photon counting with a cold telescope in space. His research involves all aspects of the instrument including developing ultrasensitive superconducting resonator detectors and the supporting readout technology. He is also collaborating with the X-ray calorimeter group to incorporate a microwave SQUID multiplexing readout in X-ray calorimeters. Through his work, he hopes to improve and scale NASA's astrophysics detector array technologies to the next generation.



# ExoPlanets and Stellar Astrophysics Laboratory



Dr. Karl Stapelfeldt  
*Lab Chief*

## Laboratory Overview

The Exoplanets and Stellar Astrophysics Laboratory (Code 667) studies the formation and evolution of stars and planetary systems using advanced telescopes and theoretical techniques. Laboratory staff support both the Hubble Space Telescope and the James Webb Space Telescope projects and are developing new instrument and space mission concepts toward the goal of searching for habitable exoplanets around nearby stars. Key areas of research include exoplanet imaging, studies of protoplanetary and debris disks, ultraviolet astrophysics, and numerical modeling of planetary system evolution. In addition to the civil service staff, the laboratory contains 28 contract scientists, post docs, and graduate students.

## Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Richard Barry	Exoplanet microlensing, instrumentation	WIRST-AFTA	Study Scientist
Charles Bowers	Instrumentation	JWST	JWST Deputy Observatory Project Scientist
Kenneth Carpenter	Stellar ultraviolet spectroscopy	HST WFIRST-AFTA	Operations Project Scientist Study Scientist
Mark Clampin	Exoplanetary systems, instrumentation	JWST, TESS	JWST Observatory Project Scientist, TESS mission co-I
William Danchi	Infrared interferometry, exoplanets	LBTI	LBTI science team
Daniel Gezari	Infrared instrumentation	Emeritus	Emeritus
Theodore Gull	Ultraviolet spectroscopy, massive stars	HST	HST/STIS Deputy PI
Sara Heap	Ultraviolet spectroscopy, exoplanets	HST	HST/COS Science Team
Randy Kimble	Instrumentation	JWST HST	JWST Integration and Test Project Scientist, HST/WFC3 instrument scientist
Marc Kuchner	Circumstellar disk theory, coronagraphy, exoplanets	WFIRST-AFTA Exo-S	Study Scientist Exo-S STDT
Richard Lyon	Coronagraphy, wavefront control, interferometry		Coronagraph technology development

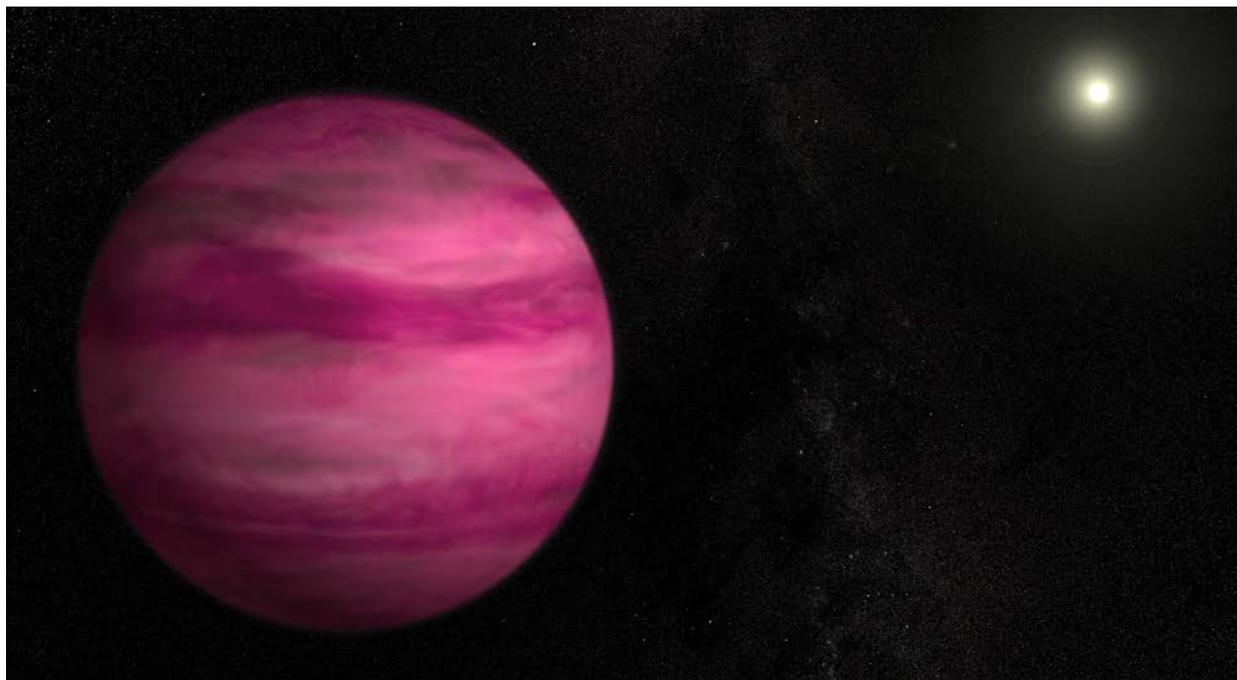
Scientist	Research Interest	Project/Mission	Role/Affiliation
Michael McElwain	Exoplanetary systems, integral field spectroscopy	WFIRST-AFTA Exo-C JWST	Study Scientist Exo-C STDT JWST Deputy Observatory Project Scientist NASA Roman Tech Fellow
Malcolm Niedner	Cometary plasmas	JWST	JWST Deputy Senior Project Scientist – Technical
Aki Roberge	Circumstellar disk observations, exoplanets	WFIRST-AFTA Exo-S LBTI	Study Scientist Exo-S STDT LBTI Science Team NASA Astrophysics Roadmap
Karl Stapelfeldt	Circumstellar disk observations, exoplanets	Exo-C LBTI	Exo-C STDT Chair LBTI Science Team
Allen Sweigart	Stellar interior modeling		Emeritus
Jennifer Wiseman	Star formation	HST	HST Senior Project Scientist
Bruce Woodgate	Ultraviolet detectors, integral field spectroscopy	HST/STIS PI	Emeritus

## SCIENCE HIGHLIGHTS

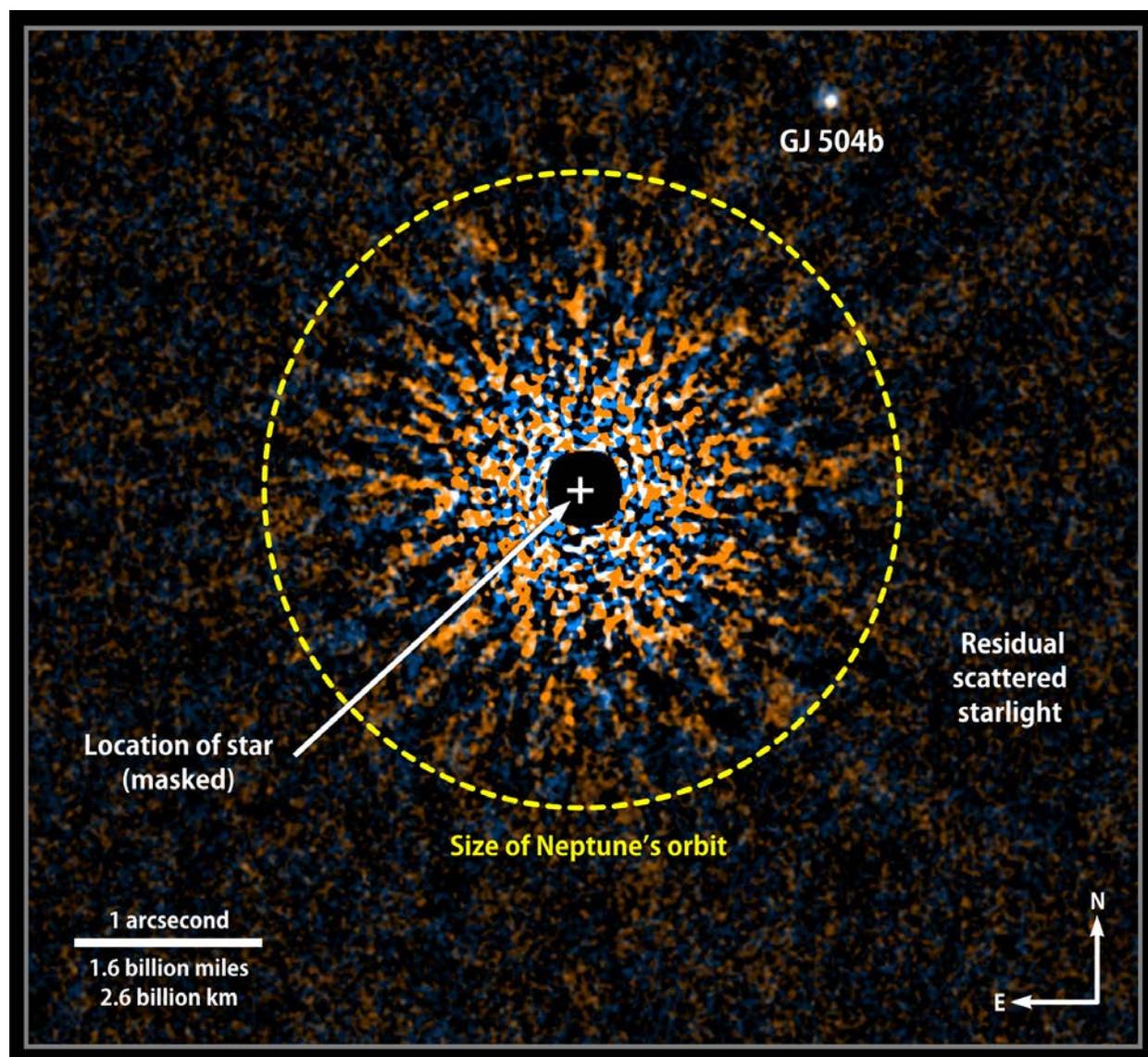
### Lowest-mass Exoplanet Imaged Around a Sun-like Star

Michael McElwain and Carol Grady of the Exoplanets and Stellar Astrophysics Laboratory were part of an international team of astronomers

led by Dr. Masayuki Kuzuhara (Tokyo Institute of Technology) that discovered a giant planet around the bright star GJ 504 using infrared data from the Subaru Telescope in Hawaii. At several times the mass of Jupiter and similar in size, the new exoplanet, named GJ 504 b, is the lowest-mass planet ever detected around a star like the sun using direct imaging techniques.



*Glowing a dark magenta, the newly discovered exoplanet GJ 504b—illustrated here in an artist's depiction—weighs in at about four times Jupiter's mass, making it the lowest-mass planet ever directly imaged around a star like the sun. Credit: NASA's Goddard Space Flight Center/S. Wiessinger*



This composite merges Subaru images of GJ 504 using two near-infrared wavelengths (orange, 1.6 micrometers, taken in May 2011; blue, 1.2 micrometers, April 2012). Once processed to remove scattered starlight, the images reveal GJ 504b. Credit: NASA's Goddard Space Flight Center/NAOJ

While direct imaging is arguably the most important technique for observing planets around other stars, it is also the most challenging due to the extreme contrast between the exoplanet and its host star, in this case  $10^{-6}$ , and small angular separations on the sky. Direct imaging of an exoplanet enables observations of the planet's projected separation and spectrum, which can be used to infer its mass and atmospheric properties such as temperatures, composition, structure, and dynamics.

GJ 504 b is about four times more massive than Jupiter and has an effective temperature of about 237 C. This exoplanet is much bluer than other imaged planets, which suggests that its atmosphere has fewer clouds. It orbits the G0-type star GJ 504,

which is slightly hotter than the sun and is faintly visible to the unaided eye in the constellation Virgo. The system lies 57 light-years away and the team estimates an age of about 160 million years based on methods that link the star's color and rotation period to its age.

GJ 504 b orbits its star at nearly nine times the distance Jupiter orbits the sun, which poses a challenge to theoretical ideas of how giant planets form. According to the most widely accepted theory, called the core-accretion model, Jupiter-like planets get their start in the gas-rich debris disk that surrounds a young star. A core produced by collisions among asteroids and comets provides a seed, and when this core reaches sufficient mass, its gravitational pull

rapidly attracts gas from the disk to form the planet. While this model works fine for planets out to where Neptune orbits, about 30 AU, it's more problematic for more distant planets. GJ 504 b lies at a projected distance of 43.5 AU from its star; the actual distance depends on how the system tips to our line of sight, which is not precisely known. The discovery suggests a different mechanism may be responsible for its formation, possibly disk fragmentation or gravitational instability.

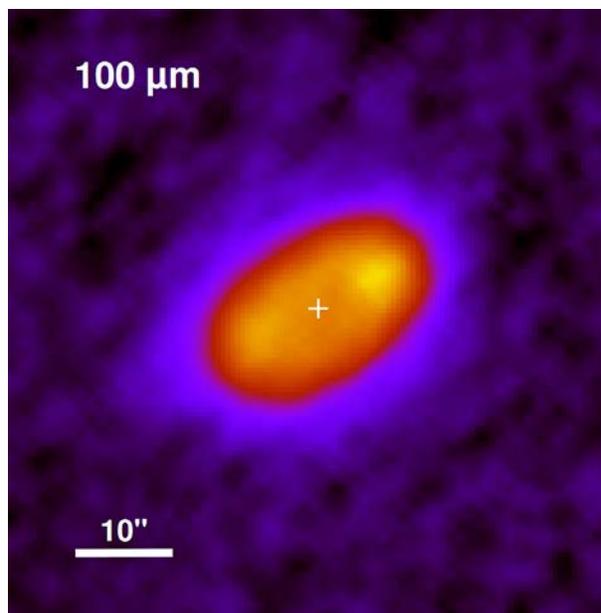
The research is part of the Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS), a project to directly image exoplanets and protoplanetary disks around several hundred nearby stars using the Subaru Telescope. The five-year project began in 2009 and is led by Motohide Tamura at the National Astronomical Observatory of Japan (NAOJ).

### Herschel completes major debris disk survey

The European Space Agency's Herschel Space Observatory successfully completed its science mission in May 2013, when its liquid helium coolant was exhausted. Goddard scientists have been involved in numerous Herschel observing projects, including two Key Projects for which summary results were reported in 2013.

DUNES (DUST around NEARby Stars) used the PACS photometer to survey a sample of 133 nearby, solar-type stars for far-infrared excess emission from a circumstellar disk. Twenty percent of these targets were found to have cool dust in exo-Kuiper belts. The Herschel/DUNES results surpass earlier Spitzer work by detecting fainter disks, finding a significantly higher disk frequency, and by spatially resolving the disk diameters in roughly half the targets. The DUNES survey shows that exo-Kuiper belts come in a range of sizes and dust content comparable to or greater than that of the sun's. Code 667 scientists Bill Danchi, Aki Roberge, and Karl Stapelfeldt participated in this work as members of the DUNES science team.

GASPS (GAS Survey of Protoplanetary Systems) used the PACS instrument to survey 250 young stars for atomic oxygen emission and explore its relationship to disk dust content. The gas detection statistics show half of stars younger than 4 million years possess gas disks, as expected. The detection rate becomes very small for stars aged 5 to 10 million years, and there are no detections at all around stars older than 10 million years. These results define the



*This Herschel PACS image at a wavelength of 100 microns reveals the far-infrared dust ring around HD 207129 (white cross), from J. P. Marshall et al. (2011). North is up, east is left and the scale bar corresponds to 160 AU*

dissipation timescale for gas in a protoplanetary disk and thus are an important constraint on planet formation models. Code 667 members Danchi, Roberge, and Carol Grady participated in this work as members of the GASPS science team.

## PROJECTS IN OPERATION

### The Hubble Space Telescope (HST)

Hubble's science return continued to soar in 2013. The Hubble Project maintained support for a full suite of science instruments, including the Wide Field Camera 3 (WFC3) developed at Goddard and the Cosmic Origins Spectrograph (COS), both installed in the most recent servicing mission, as well as the older Advanced Camera for Surveys (ACS), the Space Telescope Imaging Spectrograph (STIS), and the Fine Guidance Sensor (FGS), which can be used for some astrometric observations.

Hubble scientists are continuing to develop new, creative ways of pushing the frontiers of discovery with HST. A major goal for Hubble before its launch was the determination of the Hubble constant, uncertain then by nearly 50 percent. With sensitive measurements enabled by the WFC3, we now know this value to be  $73.8 \pm 2.4$  km/s/Mpc, a precision

## Horsehead Nebula in Infrared

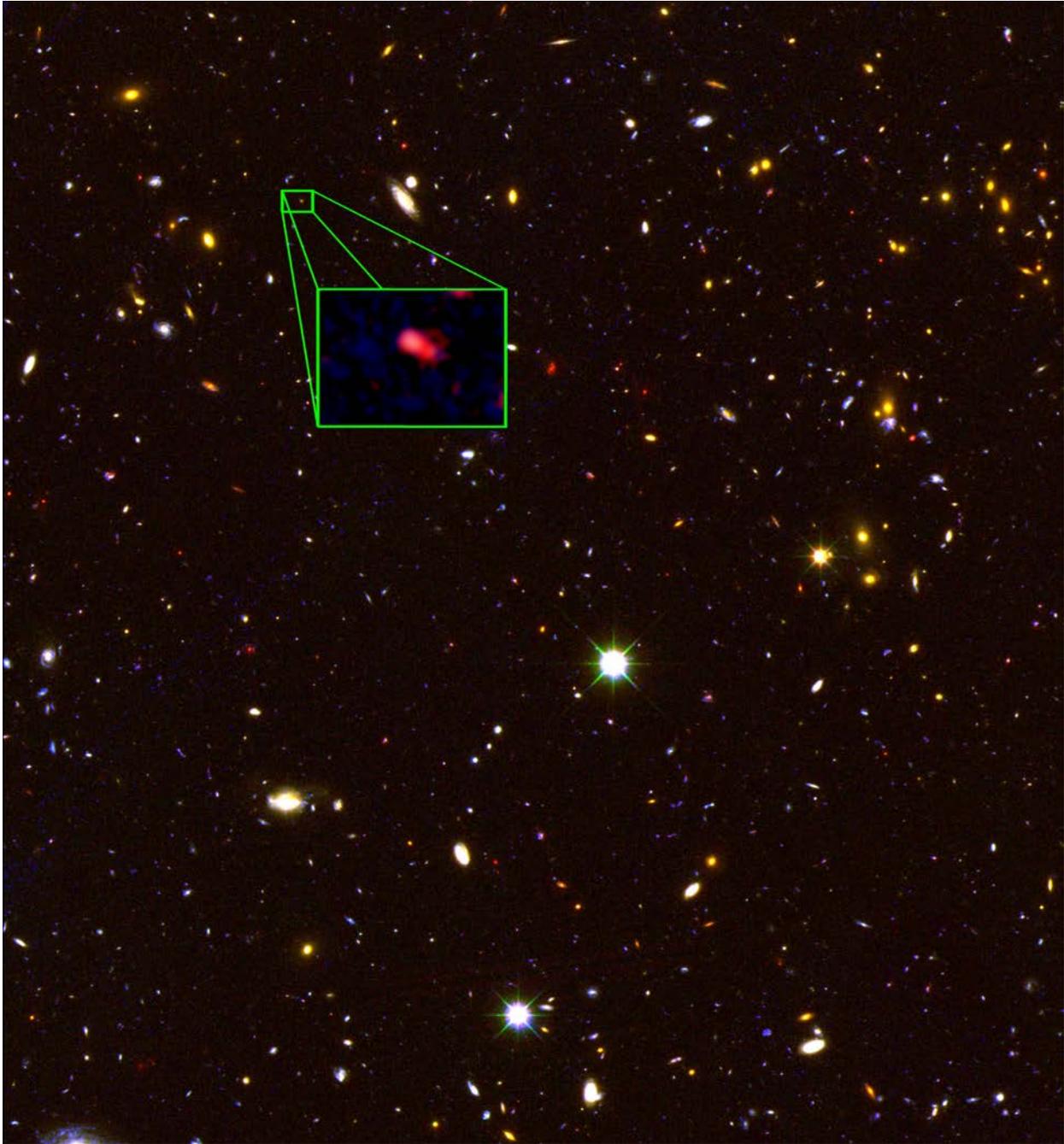
Hubble  
HeritageNASA, ESA, and the Hubble Heritage Team (STScI/AURA)  
HST WFC3/IR • STScI-PRC13-12a

Hubble imaged a “Horsehead of a different color” by producing this spectacular ethereal infrared image using the Wide-field Camera 3, developed at Goddard. The image was released in April 2013 to celebrate Hubble’s 23rd anniversary. Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

of 3.3 percent. A new scanning technique developed for use this year with the FGS and WFC3 will enable a 1-percent precision measurement of the Hubble constant within the next two years, allowing

tighter constraints on dark energy and related cosmological parameters.

Hubble is expanding the cosmic frontier further with a multi-year Frontier Fields observing cam-



*This galaxy, detected in Hubble's Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), was then studied with the Keck telescope in Hawaii to measure its redshift precisely using spectroscopy. Seen from a time just 700 million years after the Big Bang, this redshift 7.51 galaxy is at the farthest distance ever confirmed. Credit: NASA, ESA, V. Tilvi (Texas A&M Univ.), S. Finkelstein (Univ. of Texas, Austin), and C. Papovich (Texas A&M Univ.)*

paign that began this year. Taking advantage of its exquisite imaging and the natural magnification due to gravitational lensing by massive galaxy clusters, Hubble is observing previously unseen populations of galaxies and mapping dark matter, reaching galaxies with intrinsic luminosities 10–100 times

fainter than those detected in the Hubble Ultra Deep Field. Synergistic observations with Spitzer, Chandra, and other observatories will maximize the scientific potential of these observations and establish a multiwavelength legacy for these fields in preparation for JWST.



*This graphic shows the location of water vapor plumes detected by HST over Europa's south pole. While Hubble didn't image the plumes, it spectroscopically detected auroral emissions from oxygen and hydrogen with the STIS instrument, which was repaired during Servicing Mission 4. Credit: NASA, Voyager and Galileo (Europa image), ESA, and L. Roth (Southwest Research Institute and Univ. of Cologne, Germany)*

Cosmic distances were probed with Hubble this year by spotting the farthest supernova ever detected (at a redshift of 1.9, exploding 10 billion years ago), and by finding a galaxy with the farthest distance ever confirmed spectroscopically, at a redshift of 7.5 (i.e., seen from when the universe was just

5 percent of its current age). Closer to home, in a very exciting detection, Hubble found what is likely to be water vapor venting off of the jovian moon Europa. Hubble also tracked incoming comet ISON, and an asteroid sprouting six comet-like tails.



*Hubble tracked incoming Comet ISON (C/2012 S1) throughout 2013 as it dramatically brightened on its trek toward the sun. Credit: NASA, ESA, J.-Y. Li (Planetary Science Institute), and the Hubble Comet ISON Imaging Science Team*

The Project Science Office for HST at Goddard continued its science leadership with ASD scientists Jennifer Wiseman as Senior Project Scientist, Kenneth Carpenter as Operations Project Scientist, Patricia (Padi) Boyd as Deputy Operations Project Scientist, and Jeffrey Kruk as Observatory Project Scientist. Project Scientists worked with Goddard Project Management and engineering teams as well as STScI science and technical staff throughout the year on issues ranging from oversight of the telescope proposal selection and time-allocation reviews to technical status meetings. After more than two decades of successful operations, the HST Project, including the Project Science Office, convened a Review Board in the summer of 2013 to look proactively at improvements that could be made to ensure continued mission success in the coming years. The Review Board found that the processes for conducting development and operations both at STScI and Goddard appear to be generally sound, resulting in the overall high success rate for conducting operations.

### **Large Binocular Telescope Interferometer (LBTI)**

LBTI is a NASA-funded instrument deployed on the twin 8m telescope on Mount Graham in Arizona. LBTI operates at 10  $\mu\text{m}$ , nulling out the starlight

to reveal any extended emission from exozodiacal dust. In December 2013, LBTI achieved its first on-sky measurements with stabilized fringes, setting the stage for science results in 2014. In Code 667, Danchi, Roberge, and Stapelfeldt are members of the LBTI exozodi Key Science Team.

## **PROJECTS IN DEVELOPMENT**

### **James Webb Space Telescope**

The James Webb Space Telescope (JWST) is a large (6.5m), cold (50K), facility-class, general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point. It is the successor to the Hubble and Spitzer space telescopes. A summary of the JWST Project is reported in the **Observational Cosmology Lab (665) section** and includes participation by Code 667 members Bowers, Clampin, Kimble and Niedner.

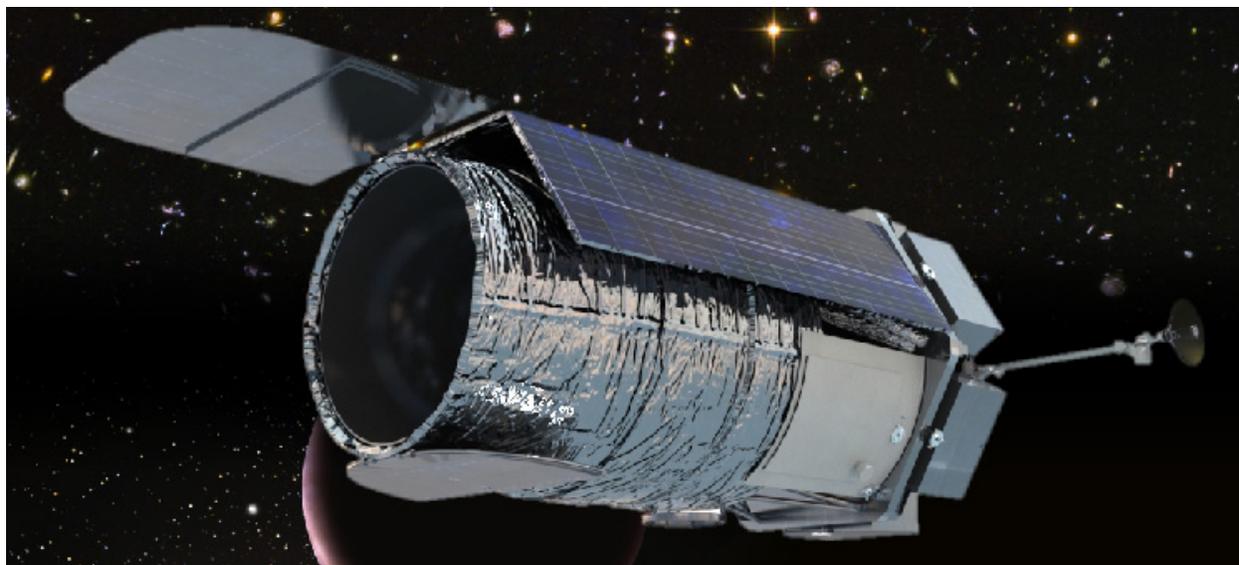
### **Transiting Exoplanet Survey Satellite (TESS)**

TESS is an Explorer mission that was selected for development in 2013. Upon its 2017 launch, TESS will conduct a two-year all-sky survey for short-period transiting planets around several hundred thousand bright ( $V=4-12$ ) stars. In conjunction with ground-based follow-up, TESS will determine the exoplanet mass-radius relation and identify the best targets for transit spectroscopy with JWST. Goddard manages the mission development for mission PI George Ricker at MIT. Code 660 involvement includes Project Scientist Stephen Rinehart and mission science co-Is Rinehart and Mark Clampin.

## **MISSION AND INSTRUMENT CONCEPTS**

### **Wide Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA)**

The Astro 2010 report New Worlds, New Horizons (NWNH), released August 13, 2010, selected the Wide-Field Infrared Survey Telescope (WFIRST) as the top priority for large space missions in the coming decade. This mission combines dark energy sci-



*This figure illustrates many features of the 2.4m WFIRST-AFTA observatory presently under study: recloseable aperture doors, solar array/sunshield, one of two instrument radiators, spacecraft bus, and one of the two deployed gimbaled K $\alpha$ -band antennas. The instruments and spacecraft bus modules are flight serviceable.*

ence with observing programs to obtain a census of exoplanets by means of microlensing and to obtain a wide range of near-infrared surveys. WFIRST is

now in pre-Phase A study, and NASA Headquarters designated Goddard as the lead center for managing the project.



*ASD outreach: Visitors learn about JWST during Maryland Day at the University of Maryland College Park from JWST Observatory Manager Keith Parrish (Code 443) on April 27, 2013. Credit: NASA/Goddard Space Flight Center/Pat Izzo*

The availability of two 2.4m telescopes from the National Reconnaissance Office (NRO) for use by NASA was announced in mid-2012, and an informal workshop on the use of these telescopes was held at Princeton in early September. Both ASD's Neil Gehrels and Jeffrey Kruk presented at the workshop, which resulted in a whitepaper (<http://arxiv.org/pdf/1210.7809v2.pdf>). A Science Definition Team was appointed by NASA HQ in October 2012 to investigate use of an NRO telescope for WFIRST (the Astrophysics-Focused Telescope Assets, or AFTA, concept). Gehrels and David Spergel of Princeton are the co-chairs. The SDT charter included consideration of a coronagraph instrument in addition to the baseline wide-field NIR survey instrument. The SDT released its first report ([http://wfirst.gsfc.nasa.gov/science/sdt\\_public/WFIRST-AFTA\\_SDT\\_Final\\_Report\\_Rev1\\_130523.pdf](http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Final_Report_Rev1_130523.pdf)) in April 2013, which described how AFTA would improve upon the prior mission concepts for the core scientific objectives laid out in NWNH and enable compelling new science programs that would not be possible with the earlier designs. Based in part on the results of this study, the NASA Administrator approved continued development of the AFTA concept for WFIRST.

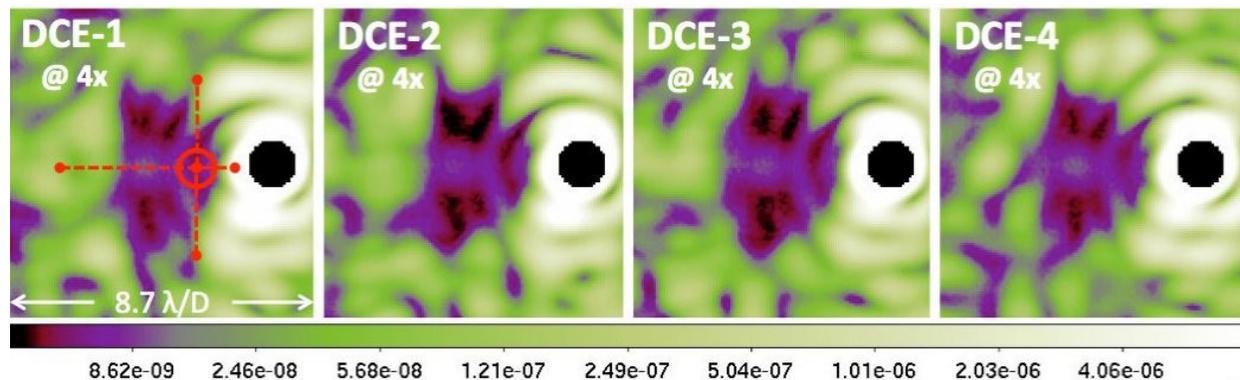
In the fall of 2013, an intensive series of workshops was held to evaluate potential concepts for a coronagraph instrument on WFIRST. The recommendation arising from this study, accepted by NASA HQ, was to develop an Occulting Mask Coronagraph (OMC) for the baseline design, which would include sets of masks to enable selection of either a shaped pupil or hybrid Lyot configuration. An alternative architecture, the Phase-Induced

Amplitude Apodization coronagraph, will be developed in parallel; this concept offers the possibility of higher performance than the OMC but is technically less mature. A final selection will be made at the conclusion of the study.

The WFIRST Project science team at Goddard includes Neil Gehrels (Project Scientist), Jeffrey Kruk (Instrument Scientist), John Baker, Rich Barry, Ken Carpenter, Brad Cenko, Marc Kuchner, Mike McElwain, Debbie Padgett, Andy Ptak, Bernie Rauscher, Aki Roberge, Amber Straughn, Eric Switzer, and Ed Wollack. This team joined the engineers from the Project Office in working with the SDT to study the implementation of WFIRST. Gehrels and Rauscher are members of the SDT. The Mission Project Office is at Goddard, supported by telescope and coronagraph teams at JPL.

### Visible Nulling Coronagraph

The Visible Nulling Coronagraph (VNC) is a hybrid coronagraphic/interferometric approach to detecting and characterizing exoplanets. The Goddard VNC laboratory test bed achieved  $5.5 \times 10^{-9} \pm 8 \times 10^{-11}$  contrast at an inner working angle of two optical resolution elements, i.e.,  $2 \lambda/D$ . This is the deepest contrast of any nulling interferometer and simultaneously at the smallest angular separation. These results were initially reported at a SPIE conference, subsequently reviewed and accepted by the Exoplanet TAC and published in "Visible Nulling Coronagraph Technology Maturation: High Contrast Imaging and Characterization of Exoplanets, Final



Focal plane high-contrast regions for 4 Data Collection Events (DCE). The central core (dark circle) is masked to compress the image range for display. The open red circle on the lower left panel shows a  $1 - \lambda/D$  diameter mask centered on  $-2 \lambda/D$  – this is the region over which that the contrast and its statistics are calculated for this milestone and the region for which the control modes are most concentrated.

Report to NASA Technical Advisory Committee” in 2013.

The next steps are (i) to increase the spectral bandwidth from 1.2 nm to 40 nm as part of the ongoing SAT/TDEM, and to ultimately increase the bandwidth to >100 nm FWHM, and, (ii) to increase the high contrast field-of-view (aka, dark hole) such that entire solar systems and dust/debris disks can be seen and characterized all at once. The FY14 VNC efforts are primarily concentrated on increasing the spectral bandwidth through the design, fabrication, and assembly of Achromatic Phase Shifters (APS). As part of the FY12/13 SAT the VNC team designed custom APS that are will be undergoing fabrication and coating using IRAD funds. Additionally a new NPP postdoc will lead both the fabrication and test effort.

A phase-occultation VNC (PO-VNC) would decrease the sensitivity to telescope misalignment and instability and increase the field of view. The fabrication of optics for the PO-VNC are funded under Goddard FY14 IRAD and a TDEM will also be submitted for this work. The PO-VNC allows wider field-of-view high-contrast imaging with no moving components. Increasing the spectral bandwidth is necessary for the spectroscopy needed for exoplanet characterization. Increasing the high-contrast field-of-view and decreasing the sensitivity to telescope instability allows more exoplanets to be characterized and/or less stressing tolerances on the telescope design.

### **Exoplanet Direct Imaging Probe Mission Studies (Exo-C and Exo-S)**

In spring 2013, NASA chartered two mission studies in the \$1 billion class to serve as lower-cost alternatives to WFIRST-AFTA. NASA HQ selected four members of Code 667 to serve on the study Science and Technology Definition Teams: Stapelfeldt (chair) and McElwain for the Exo-C coronagraph and Kuchner and Roberge for the Exo-S starshade. Both teams met three times to develop their science case and conduct trade studies on mission designs, working in conjunction with engineering teams at the Jet Propulsion Laboratory. Interim reports will be presented to NASA HQ in spring 2014, with final reports in early 2015.

## **TECHNOLOGY DEVELOPMENT**

### **Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies (PISCES)**

Development of a high-contrast optical integral field spectrograph was initiated in mid-2013 when McElwain’s proposal was selected. PISCES will be integrated at Goddard and delivered to the JPL High Contrast Imaging Testbed in 2015. It is a prototype of the backend instrument selected for the AFTA coronagraph and is expected to fly on a future New Worlds exoplanet imager. PISCES will demonstrate technical readiness for this instrument type and serve as a diagnostic tool for broad-band coronagraphy.

### **Ultraviolet Detectors**

With support from NASA APRA, Bruce Woodgate, Tim Norton, George Hilton, and Joe Stock are developing a detector concept that combines high quantum efficiency photocathode materials, magnetic focusing of the photoelectrons, and a CMOS readout in  $2K \times 2K$  format.

## **AWARDS**

In 2013, Bruce Woodgate won NASA’s Distinguished Service Medal, the agency’s highest form of recognition, awarded for individual achievements or contributions that have a profound impact on NASA mission success. The previous year he had won the Robert H. Goddard Award of Merit in 2012 “for exceptional career achievements in science and service to Goddard and NASA.”

The agency also recognized the work of Mark Clampin with the 2013 Exceptional Achievement Medal, awarded to any Government employee for a significant, specific achievement or substantial improvement in operations, efficiency, service, financial savings, science, or technology which contributes to the mission of NASA.

The 2013 Goddard Honor Awards for Science went to Aki Roberge “for excellence in original research on exoplanets and planet formation, and strategic service to NASA astrophysics” and to

Charles Bowers “for contributions to the scientific performance of the James Webb Space Telescope.”

NASA established the Nancy Grace Roman Technology Fellowship in Astrophysics in 2011 to foster new talent by putting early-career instrument builders on a trajectory toward long-term positions. The Roman Fellowship is structured into three components. The first is an initial one-year Concept Study to generate the detailed plans and commitments for developing the proposed astrophysics technology. The final report from the Concept Study, due nine months after the start of the award, will be peer reviewed to select Fellows to continue in a four-year Development Effort that will implement the study plans. Finally, an opportunity is available to Fellows in the four-year Development Effort to apply for start-up funds when they obtain a tenure-track, permanent civil service or equivalent position. Code 667’s Michael McElwain was among three scientists selected for a concept study in the first year of the award. NASA Headquarters evaluated the proposals in 2013 and selected his integral field spectrograph project, named PISCES, for development and ultimate deployment on the High Contrast Imaging Testbed at JPL. The instrument will lay the ground work for a similar space-based capability to characterize exoplanetary atmospheres.

## NEW FACES

### Christopher Stark



Christopher first arrived at Goddard in 2005 as a NASA GSRP Fellow, and has recently returned as an NPP fellow. After graduating with a Ph.D. in physics from the University of Maryland in 2010, Chris spent three years as a Carnegie Fellow at the Department of Terrestrial Magnetism. Chris’

work spans a wide range of interests, from exoplanet detection and debris disk studies to theoretical dust dynamics and future mission planning. Working with Roberge, Chris has created the Design Reference Mission simulator for the ATLAST mission concept and developed methods to increase the yield of extrasolar Earth-like planets. At Goddard, Chris will continue to help define the ATLAST mission design, constrain the composition of extrasolar planetesimals in resolved nearby debris disks, and investigate the impact of interplanetary dust structures on future exoplanet imaging missions.

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